SUSTAINABLE ENERGY OPTIONS FOR THE FUTURE AIRPORT METROPOLIS

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Submitted in fulfilment of the requirements for the degree of
Master of Engineering (Research)

Science and Engineering Faculty
Queensland University of Technology

2016

Keywords

Airport Metropolis, Efficiency, Energy, Renewable, Sustainable, Decision-making, DSS.

Abstract

Recently the aviation industry has experienced unprecedented growth both on the airside (in terms of increased aircraft movements) and on the landside (in terms of the development of large Airport Metropolises). Increased use of fossil fuels is linked with dangerous climate change.

One of the main strategies for mitigating the aviation industry's impacts on the environment is to make the energy use practices on the landside more sustainable. This paper presents a variety of sustainable energy options that are suitable for airport facilities. It also analyses decision making processes and software packages that can assist to achieve this goal. The significance of this research is that it will assist airport operators to make improved sustainable energy decisions concerning the development of their airport.

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Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: QUT Verified Signature

Date: February 2016

Acknowledgments

I would like to acknowledge and thank my supervisors Professor John Bell, Adjunct Professor David Hood and Dr Arron Walker, who were always very generous with their time. Their expertise and support helped me greatly, and I am appreciative of their feedback and suggestions.

I would also like to thank my wife Belinda, and three children Joshua, Cooper and Lily, for being supportive and understanding as I undertook this research while also working.

In addition I would like to thank Matthias Anker from Infinity Power for providing commercial information related to solar PV projects.

Chapter 1: Introduction

This chapter outlines the background (section 1.1) and context (section 1.2) of this research, and its purposes (section 1.3). Section 1.4 describes the methodology, followed in section 1.5 by a discussion of the significance and scope of this research. Finally, section 1.6 includes an outline of the remaining chapters of the thesis.

1.1 BACKGROUND

QUT is a major partner in an international collaborative research project entitled Airport Metropolis – Managing the Interfaces. As described on the project's web-site, "The primary role of this project is, from a multi-disciplinary perspective, to investigate and make an integrated response to four major interface issues of the new 'airport metropolis'"[1].

The four interfaces investigated within the scope of this project are:

- Economic Development
- Land Use
- Infrastructure
- Governance

The research conducted for this thesis falls within the Infrastructure focus of the Airport Metropolis project.

A more comprehensive discussion of Airport Metropolises will proceed in later sections, but initially it can be defined as an "Airport City". As airports around the world have grown, they have extended beyond a traditional transport footprint to provide services and facilities in leisure, commerce, retail and other areas.

And as with any other "city" their demand for energy resources increases as they develop. As the world grapples with issues related to energy use such as human-induced climate change, and depletion of non-renewable energy sources such

[1] http://www.airportmetropolis.qut.edu.au/outline/introduction.jsp

as fossil fuels, it is relevant for Airport Metropolises to consider how they can move to more sustainable energy practices.

1.2 CONTEXT

This research is set against the context of global demand for energy that is ever-spiralling upwards. An Airport Metropolis is a significant user of energy resources. And in addition to the energy use that they are directly responsible for that occurs on the land-side of airports, they are also closely associated with the energy use that occurs on the air-side. While this latter energy consumption is the responsibility of the airline companies and operators, airports would not exist if this consumption did not occur.

Most Airport Metropolises are private businesses. In fact, the move by Governments to privatise airports is one of the drivers behind the evolution of the Airport Metropolis. It is clearly in the interests of airport operators, if they wish to have long-term sustainable businesses, and maintain their community "licence to operate", that they increase (and are seen by the paying public to increase), the sustainability of their energy use.

There is a need for research that assists Airport Metropolis stakeholders to streamline and optimise the decision making process around sustainable energy use.

1.3 PURPOSE/AIM OF RESEARCH

The objective of this research is to meet this need by investigating and creating a unified decision support framework and resource kit that can be beneficial to Airport Metropolis decision makers as they seek to improve the sustainability of their energy use.

The goal of the framework is to provide an end-to-end process that can be followed to support decision making, and the goal of the resource kit is to identify specific tools and techniques that can be used at each step of the process.

In order to make the results as broadly usable as possible, any software tools will be screened to select only those that are freely available and do not impose any licensing fees. Consideration is also given to the suitability of components for inclusion in future work. For example, a decision support system could be built that incorporated the framework and resource kit presented here.

1.4 METHODOLOGY

The following methodology summarises the steps involved in conducting the research:

- Literature/environment scan, initially targeted at typical characteristics and energy use patterns of Airport Metropolises, available RET and energy efficiency options, and decision support frameworks.
- Further scanning in areas identified to be common elements of the decision process, including sustainability indicators, reporting frameworks, standards, knowledge bases, selection tools and decision analysis tools.
- Review and identify an overarching decision framework, and specific tools and techniques for inclusion in a resource kit.
- Conduct case study assessment of key components of resource kit to confirm viability and acceptability, and provide an example of usage.

1.5 SIGNIFICANCE, SCOPE AND DEFINITIONS

This research is important as it helps to bridge the knowledge gap that impedes Airport Metropolis decision makers from evaluating, instigating, and implementing through to completion, projects that increase the sustainability of their energy use. The decision makers must run large businesses and focus on a whole range of issues that impact on those businesses, including those of the airline companies who tenant their terminals. Airports are frequently in the news for security issues, flight delays and cancellations during extreme weather events, transportation issues, car-parking problems, traffic jams, bird-strikes, aircraft groundings, industrial action and so on. Even those decision makers who are determined to focus on long-range and strategic planning face a daunting challenge to achieve this given these and other day-to-day operational issues.

Research such as this that puts these decision makers in a more informed position and better able to make optimal decisions about proceeding with sustainable energy projects is of value. A good outcome would be a scenario where decision makers feel empowered to invest additional effort in exploring sustainable energy options beyond minimum regulatory and corporate requirements.

Energy prices are increasing at a dramatic pace world-wide. Electricity prices are rising as capital expenditure is committed on projects to upgrade generation, transmission and distribution systems, often to cater for peak demand, which itself may only occur a limited number of times each year. Various forms of carbon pricing are also being implemented which is also affecting energy prices.

Airport Metropolises consume large quantities of various forms of energy. With prices rising, it is highly significant that attention and focus is given to this area.

The scope of study is limited to land-side considerations of Airport Metropolises. This excludes air-side topics such as jet-fuel efficiency improvements. It also excludes smaller airports and aerodromes.

1.6 THESIS OUTLINE

This thesis is organised into 6 chapters. Subsequent to this chapter are the following chapters:

- Chapter 2 reviews the background literature
- Chapter 3 explains the research design and methodology
- Chapter 4 executes the case studies and present the results
- Chapter 5 analyses the research results
- Chapter 6 presents the conclusions from this study

Chapter 2: Literature Review

2.1 BACKGROUND

Recently the aviation industry has experienced unprecedented growth, driven by strong global economies and low cost airlines. This trend is expected to continue given the predicted growth in both China and India and the continued demand of new global market economies that require goods to be shipped quickly.

Given the increased passenger, freight and aircraft movements through airports, it is not surprising that some airports have undergone major changes. For some of the world's most successful airports, the changes are so dramatic it has given rise to a new type of airport. This new type of airport is best described as the emergence of a city metropolis around an airport transport infrastructure hub (Kasarda, 1996) (Stevens, 2006) referred to as an Airport Metropolis.

The planning philosophy behind the Airport Metropolis allows the generally vacant land immediately adjacent the airport terminals and runways to be developed into commercial and industrial activities that either support the aviation industry or support the new economy industry or improve amenities for passengers. This philosophy has been successful and has seen some airports transform themselves into self-sustaining economies which are independent of the neighbouring city they once relied upon.

Of course all this increased development activity at airports increases their potential environmental impact. This in turn has ramifications for the aviation industry which is seeking to reduce its greenhouse gas emissions and present itself as a sustainable global industry.

It is no secret that the airside of the aviation industry is a large contributor to greenhouse gas emissions (Macintosh & Downie, 2007). In addition, it would appear that no significant energy efficient jet engine technology improvements are likely in the near future (Peeters, Middel, & Hoolhorts, 2005). Therefore any immediate sustainability gains are more likely to come from the landside of the industry.

Consequently one of the main strategies for mitigating global warming within the aviation industry is to reduce the amount of energy use on the landside (i.e. at airport facilities). To achieve this goal, more sustainable energy use practices must be employed. This chapter presents a summary of available sustainable energy options and makes an assessment of those ideally suited to the Airport Metropolis context. Investigation is conducted into airports that have been innovative in adopting such options. A report is produced on indicators that are applicable to measuring sustainability of airport energy operations, and decision support frameworks are reviewed. Finally, an assessment is made of available software tools that are candidates for being incorporated into a decision support framework. But first, a look at the typical energy use characteristics of an Airport Metropolis.

2.2 ENERGY USE CHARACTERISTICS OF AN AIRPORT METROPOLIS

A large airport can consume the same amount of electricity as a city of 100,000 people (Carter & Burgess, 2002). In 2012-2013, electricity consumption at Brisbane Airport was 174 GWh (Brisbane Airport Corporation, 2013). Total purchased energy consumption in 2011 at Frankfurt Airport, one of the world’s largest, was reported against GRI category EN4 (indirect energy consumption) as 3,953 TJ. This includes 600 GWh of electricity consumption (Fraport AG, 2012).

As a consequence, airports budget for large bills from utility companies. The annual electricity budget for Seattle-Tacoma International Airport in the year 2000 was USD $6 million (Port of Seattle, 2005). In addition to electricity, airports are consumers of other energy sources. For example, natural gas can be used as a source for heating, and for powering onsite combined heat and power plants (CHP, referred to as cogeneration), and oil-based products can have uses such as heating and powering landside transportation.

These airports tend to occupy large, flat land areas. Brisbane Airport occupies land totalling 2,700 hectares (Brisbane Airport Corporation, 2003). Airports are also characterised by the type of buildings that are typically constructed. These are large buildings such as terminals, hangers, multi-story carparks, office and/or retail space, freight and logistics areas, and hotels. They are voluminous, typically with extensive roof areas (i.e. large roof to internal volume ratios) and require energy consumption for a large range of services, including ventilation, space heating/cooling, lighting, internal transport, cooking, refrigeration, communications, water heating/cooling and machines.

Another point to consider is that these airports have expanses of land covered in pavement-based surfaces - runways, roads, carparks, walkways and so on. These are often dark surfaces, such as asphalt-based ones. In warmer climates they will contribute to the urban heat island effect - increasing cooling costs for the airport during summer, yet only marginally decreasing heating costs during winter (Heat Island Group Berkeley Lab, 2007).

Airport Metropolises also operate under a number of constraints. For example:

- There is a need to ensure security of energy supply and uninterrupted operations.
- Owing to the often remote location of the airport, is it possible some supply lines are not installed, for example no reticulation of natural gas, which would be a constraint on installing a co/trigeneration system.
- A large percentage of onsite consumption is done via tenants. Existing lease arrangements may actually provide a financial incentive for the airport to have its tenants using more grid supplied power than less if they are charging a supply fee. Or there may be limited incentives for the airport to make energy efficiency improvements if the main beneficiary is the tenant.
- Highly regulated environment, which may limit options available.
- Current economic management standards may preclude certain options. For example a minimum IRR may preclude an RET installation. Other life cycle cost assessment methodologies may need to be incorporated.

2.3 SUSTAINABLE ENERGY

Sustainable energy refers to energy sources which can be converted into useful forms of energy without adversely affecting vital ecological support systems for life on earth (i.e. the planet's climatic system). Previous research points to renewable energy and energy efficiency as the twin pillars of sustainable energy use (Prindle, 2007). Renewable energy focuses on the supply side of the energy equation, while efficiency relates to the demand side. Both pillars are potential options for Airport Metropolis type developments.

A desktop study of current literature regarding the various renewable supply and demand reduction sustainable energy techniques was conducted. The aim of the study was to determine which techniques would be suitable for Airport Metropolis type developments. The relative merits and disadvantages of each technique are discussed in the next section.

This process will narrow the scope to focus on a number of areas that have the greatest potential significance to landside sustainable energy practices at an Airport Metropolis.

2.4 RENEWABLE ENERGY TECHNOLOGIES

Renewable Energy Technologies (RETs) are fast becoming commonplace as the effort to increase sustainable energy use practices intensifies. Many RETs are available as mature commercial products and potentially should offer a real alternative to energy generation as part of an Airport Metropolis development. RETs harness energy from the following sources (United Nations. Dept. of Economic and Social Affairs, 2001):

- Hydropower
- Biomass energy
- Solar energy
- Wind energy
- Geothermal energy

2.4.1 HYDROPOWER

Hydropower, the capture of the energy of moving water, has four primary types: stored (dams), run-of-river, tidal and wave. A typical large hydroelectric scheme is not possible in an airport context, unless the airport is located near a large body of water that contains usable kinetic energy potential. Fast-flowing rivers for small-scale run-of-river, or similar turbine based schemes, are also unlikely in the flat terrain typically chosen for airports.

Tidal barrage systems are environmentally complex given the need for structural alteration to the tidal area. Tidal stream turbine systems and wave systems do not have the same environmental complexities, and they do have proven commercial ability.

All hydropower generation options are heavily dependent on the individual airport's geographic location and right-of-access to the water deployment zone. Additionally, the environmental impact of developing a hydropower system near airports would make it unsuitable for most airport situations. Airports on reclaimed land surrounded by large ocean frontages could benefit from hydropower provided all environmental sustainability criteria were met.

2.4.2 BIOMASS

Biomass derivatives such as biogas and liquid biofuels can be purchased for onsite use. Biodiesel can be used to power onsite transportation vehicles. Munich Airport and Amsterdam Airport Schiphol are two examples of large Airport Metropolises that are running some of their ground fleet on biodiesel.

Biogas can be used as an alternative to natural gas, for example as the combustion source for heating (or cooling) of buildings, water or food.

Solid biomass, such as food waste, can be harvested by an airport and recycled onsite as an energy source, for example via gasification. Such a scheme could even be expanded to include the receipt of waste from surrounding areas.

Biomass energy is well suited to airport applications and numerous airports have successfully applied this technology. London's Stansted airport has installed a 2MW woodchip boiler in order to provide biomass supplied heating and hot water (LC Energy, 2014). The system was installed in 2008 and has been reported as performing above expectations (London Stansted Airport, 2014).

At Heathrow Airport in London, the T2 energy centre is a combined heat, and power plant (CHP) which is powered by biomass. The biomass fuel is sourced from sustainable forests located within 150 kilometres of the airport. The system has a capacity of 10 MW (LC Energy, 2014). These systems are sustainable because they maintain a closed carbon cycle with no net increase of carbon to the atmosphere and no net depletion of resources if the harvested crop is replenished.

Another airport in England, East Midlands, plans to fuel a terminal boiler with biomass grown onsite. 26 hectares of willow trees have been planted on the airport site (East Midlands Airport, 2010).

Aeroports de Paris in 2012 installed a 14MW wood-burning boiler at Charles de Gaulle airport. It is supplying 25% of the airports heating requirements, and is reducing CO_2 emissions by 18,000 tonnes per year (Aeroports De Paris, 2012).

2.4.3 SOLAR

Solar energy is very relevant to airports, and indeed there are numerous working examples of utilisation of this form of energy in an airport setting. Solar energy can be harnessed via photovoltaic cells, which directly produce electricity, and via solar thermal systems, which produce heat which can be used directly (for space or water heating) or converted to electricity.

The physical characteristics of airports support the harnessing of solar energy. Large land areas are possibly available for solar farms, and large buildings exist with roof areas that can be equipped with solar collectors. In addition, passive solar systems are also relevant for use at airports, and these are discussed in the energy use minimisation section.

Solar photovoltaic

Increasingly, airports are adopting solar PV technology. Airport buildings are frequently built in physical dimensions that are both large and horizontally expansive. This opens up opportunities for building integrated photovoltaics (BIPV) and building applied photovoltaics (BAPV) given the large external surface area that is sun-facing. This can be contrasted with office buildings in the central business districts of most cities.

It has been shown that the integration of PV systems on typical airport buildings in sunny climates with high irradiation levels can supply the entire electric power consumption of the airport precinct (Ruther & Braun, 2009). This study was based on Florianopolis International Airport in Brazil (27°S, 48°W), where average solar irradiation ranges from 1550 to 1650 kWh/m^2. A 1670 kWp installation would make the airport a net energy exporter based on actual demand data from 2005-2006 assessed on a month-by-month basis. There is a strong correlation between ambient temperature, electricity demands (largely from air conditioning), and solar radiation availability in such climates.

The adoption of PV technology is also appealing in the airport context because it is a highly visible statement of commitment towards sustainability.

In addition to BIPV/BAPV systems, airports can also install open field systems. One of the world’s largest open field airport installations is at the Fresno Yosemite International Airport in California. *Figure 2.1* displays an image from Google Maps showing the site of the installation (highlighted by a rectangle in the bottom-right corner).

Figure 2.1. Solar PV installation at Fresno Yosemite International Airport, CA, USA.

The solar installation land area is 2.5 hectares in size and is unsuitable for other types of development because it is near the end of the runway. The solar panel system comprises 11,700 panels, installed on an east-west tracking system, and has a rated capacity of 4.2 MW.

As an interesting aside, the map also shows a golf course in the top section (“Fresno Airways Golf Course”). This is another attribute of the modern Airport Metropolis, branching into leisure activities like golf.

Another American airport, Denver International Airport, has implemented single-axis tracking solar field installations over a number of project phases and is now totalling 8 MW in capacity, capable of meeting over 6% of the airport’s energy demand in 2011 (SustainableBusiness.com, 2011). The images in *Figure 2.2* depict these installations.

a)

b)

Figure 2.2. a) and b) Solar field installations at Denver International Airport

These images from Denver serve to reinforce the point that such installations are often highly visible statements to the public of the airports commitment to sustainable energy. In the case of Denver, major airport arterial highways pass very closely by the installation sites.

A further example of solar photovoltaic use in an airport context is the installation of 111 kW of solar capacity at Austin-Bergstrom International Airport.

The strategy implemented at this airport was to install the solar panels over a car park, providing an added shading benefit (Austin Energy, 2007).

At the Mineta San Jose International Airport, a large 1.12MW BAPV system became operational in 2010, delivering an annual output of 1,713 MWh (Canadian Solar, 2010). *Figure 2.3* shows the solar panels fixed to the roof-top of the airport's Rental Car Center.

Figure 2.3. Roof top solar PV at Mineta San Jose International Airport

Approximately 20% of the buildings requirements are met by the installation which comprises 4,680 panels covering an area of 3.4 acres (1.37 hectares).

Solar thermal

Solar thermal projects are not as numerous at airports as solar PV. There are, however, a number of installations that demonstrate the possibilities in this area.

Vancouver International Airport is Canada's second busiest airport. They have installed a solar hot water system on the roof of the domestic terminal.

Figure 2.4. Solar hot water system, domestic terminal, Vancouver International Airport

The system, as partially depicted in *Figure 2.4,* consists of 100 roof top panels, and heats an average of 3,000 litres per hour. No seasonal performance figures are available but it is stated to save (CAD) $110,000 per year. The airport has been able to achieve a 25% reduction in natural gas usage from this initiative, along with other related ones including night set-backs and improved scheduling (Vancouver Airport Authority, 2009).

Solar thermal electric

The future may hold greater potential for airports to adopt solar thermal technologies, especially as they are increasingly advanced and adopted in the broader economy. The characteristics of airports that makes solar PV suitable to open-field and BIPV/BAPV projects, apply equally well to solar thermal technologies.

Solar thermal energy could be used in an onsite Concentrated Solar Power (CSP) system, or Compact Linear Fresnel Reflector (CLFR) system. These systems concentrate solar energy to maximise the heating capability and then generate electricity via a steam turbine.

Looking beyond the airport context, it can be seen at present around the world that this technology is maturing. At the Andasol power plant in Spain (*Figure 2.5*), 150 MW of capacity is provided via parabolic reflector troughs, and the system is connected with molten salts which store excess heat during the day and this heat is harnessed by the thermal power engine during times when the plant would not otherwise operate such as night time and when cloud cover or rain is present.

a)

b)

Figure 2.5. a) and b). Andasol power plant, Spain.

The issue of visual interference to pilots during take-off and landing is something that should not be a concern with these systems because the reflective surfaces are focused on receivers.

Research has investigated the effectiveness of solar thermal powered absorption chillers in applications such as medium sized office buildings. When heating is required (e.g. winter), the heat from the solar collectors can be delivered to heating applications. When cooling is required, the absorption chiller can convert the heat collected for use in cooling applications. The economics of such systems are highly dependent on energy prices (Mammoli, Vorobieff, Barsun, Burnett, & Fisher, 2010). Given that these are escalating rapidly in many parts of the world, and given the shared characteristics of Airport Metropolis buildings with office buildings, the indications are that this technology is becoming increasingly relevant in the airport context. In addition, there is research available which provides guidance on optimising system configurations for the shared goals of economic performance and environmental performance (Hang, Qu, & Zhao, 2011).

2.4.4 WIND

Wind energy is potentially a very useful source of renewable energy for airports, again because the land-rich nature of airports provides many feasible onsite locations. However, air safety and/or height restriction regulations may limit the practical application of building wind turbines on, or near, airport land, for reasons of both being a physical obstacle, and radar interference.

For example, the British Civil Aviation Authority (CAA) dictates that it be notified of any planning application for a proposed wind turbine development within a 15 km radius of any aerodrome in its jurisdiction so that it and the aerodrome can carry out investigations and analysis of any potential interference (Civil Aviation Authority UK, 2003).

There is a precedent for successfully managing the installation of wind turbines at East Midlands Airport in England where two 250kW turbines have been installed and are operational. These are of a sufficiently small size, and located close to the centre of the radar, such that there are no radar or height safety issues. However, turbines planned for installation 10km from the airport have necessitated extra measures to counter shimmering distortions that can be visible on the radar caused by the turbines. The distortions are a safety issue because they can be mistaken for aircraft (BBC News, 2014).

Technical innovations are being developed with the goal of ensuring that such concerns are overcome and do not prevent wind energy-based sustainability initiatives from receiving planning approval and proceeding at or near airports (NATS, 2014).

The East Midlands turbines (see *Figure 2.6* and *Figure 2.7*) are designed to meet 5-10% of the airports electricity demands, which in 2013 was a total of 20 GWh (East Midlands Airport, 2014). The model chosen (Wind Technik Nord 250) has a hub height of 30 metres and three 15 metre blades. The total height of 45 metres fits within the maximum height under the transitional slope from the runway for the selected installation site (Howell, 2010).

Figure 2.6. Wind turbines installed at East Midlands Airport

Figure 2.7. Wind Turbine at East Midlands Airport, U.K.

There are various types of wind turbines that airports could choose to install. The East Midlands example is one of ground-mounted turbines. At Logan International Airport, Boston, twenty smaller wind turbines have been installed on the roof of an airport building. The turbines have a rated output of 1 kW each and are approximately 3 metres in height. As can be seen from the image in *Figure 2.8***Error! Reference source not found.** these small turbines can be installed as part of an array on top of buildings. The characteristics of typical airport buildings that make them suitable for solar also make them suitable for such small wind arrays.

At Logan International Airport, these turbines account for 2% of the electricity consumption of the building on which they sit, which in 2011 was approximately 100,000 kWh. This represents a reported annual saving of USD $13,000 per year and a payback period of 10 years (Boston Logan International Airport, 2013). They are angled slightly downwards in order to counteract the turbulent environment in which they operate and also to help them better capture the air flow unique to building aerodynamics (City Parks Association of Philadelphia, 2011).

Figure 2.8. Small turbines on roof of building at Logan International Airport.

Another option available to airports is the use of vertical-axis wind turbines. These turbines are compact and are suitable for installation in areas close to people and buildings. Such turbines have already been installed, as an example, at Denver International Airport (*Figure 2.9*) and Bristol Airport.

At Denver International Airport, six turbines have been installed as part of initiatives to make an onsite car parking facility more sustainable. Each turbine is 9.1 metres tall with a diameter of 1.2 metres. The rated output is 1.2 kW at a wind speed of 40 km/h (Solaripedia, 2011).

Figure 2.9. Vertical axis wind turbines at Denver International Airport

The airport chose vertical-axis turbines for this setting for a variety of reasons:

- They enabled a larger number of turbines to be placed into a small area.
- The turbines would not be impacted as much by turbulence.
- Maintenance costs would be minimised because much of the plant is located at ground level.

2.4.5 GEOTHERMAL

Geothermal energy utilises heat available in deep underground structures, or takes advantage of the heat difference available above and beneath the earth's surface. Geothermal electricity production is normally associated with extracting high temperature heat from deep wells. Heat exchangers can also utilise hot water or steam from these locations. Doing this onsite at airports is not as conveniently achievable as some of the other RETs addressed above, as it is dependent on specific geological structures existing beneath the airport such as reservoirs of hot water, or hot rocks.

Paris-Orly airport has installed a geothermal heat exchange which has been operating since 2011. Two wells were drilled to a depth of 1,750 metres. On the surface they are co-located but they diverge to be 1,400 metres apart at depth. The geothermal resource consists of water heated to 74°C. It is extracted to a titanium heat exchanger which transfers the heat to the airports hot water circuit. It is then returned to the reservoir at a temperature of 40°C.

The plant is producing 150 MWh(t)/yr which meets around 30% of the airports heating needs. This is resulting in a reduction of 9,000 tons of CO_2 emissions (Aeroports De Paris, 2012).

Geothermal or ground-source based heating and cooling has well proven applicability within an airport context and is much more widely available as it takes advantage of the relatively uniform temperature of the ground by using it as a heat sink or source. For example, a feasibility study has been conducted for the Macedonia Airport in Thessaloniki. This study concluded that a geothermal system could provide 8 MW(t) of heating or 7MW(t) of cooling capacity, with annual production of 16,800 MWh(t) (Mendrinos & Karytsas, 2003). The study included a method for comparing the costs of this system with a natural gas and diesel system and concluded that the geothermal system was characterised by high energy efficiency and competitive costs (pg. 22).

An example of an airport tenant utilising geothermal energy is the Caltex Airport StarMart at Canberra Airport. This was a greenfield site, where the payback period on installing a geothermal air conditioning system was one year (Department of the Environment and Water Resources, 2007).

Heat pumps for heating in winter and cooling in summer are becoming increasing popular, especially in some countries. In Canada, for example, the estimate of the geothermal heat sink resource is described as vast (Majorowicz, Grasby, & Skinner, 2009), and there has been considerable uptake there in recent years.

Juneau International Airport in Alaska has installed a heat pump system as part of a renovation of its main terminal building, replacing traditional diesel fired boilers. It was built between 2009 and 2011 and comprises 108 vertical borings, each to a depth of 100 metres. The total underground pipe length is 26 kilometres. The piping is connected with 31 electric heat pumps. In this regard, the system is decentralised, which is cited as an advantage in terms of maintainability.

Diesel consumption has reduced over the period from 2008 to 2011 from 340,000 litres to 200,000 litres, representing an annual saving of USD$130,529. Over the same period, electricity usage has increased from 2,093 MWh to 2,262 MWh, which represents an annual cost increase of USD$15,544. The net annual reduction in energy costs over this period is USD$114,985 (Murray & Fritz, 2012).

With increasing prices of fossil fuel-based energy, the economics of using heat pumps for controlling building air temperature are becoming more attractive. The techniques used in community/district systems, and also commercial buildings, are also of interest in the Airport Metropolis context.

2.4.6 OFFSITE RET GENERATION

An alternative to onsite RET generation is purchasing of energy from offsite RET generation. For example, some organisations such as utility companies and energy retailers offer their customers the opportunity to purchase a proportion of their energy from renewable sources, usually branded along the lines of “Green Power”. This option is only available to airports that have connectivity to “Green Power” utility companies.

Aeroports de Paris has an electricity supply contract in place that guarantees that 30% of electricity supplied will derive from sustainable French sources (Aeroports De Paris, 2012).

Dallas Fort Worth International Airport was listed in the U.S. Environmental Protection Agency’s top 20 Local Government List of the largest green power purchasers in 2013. It purchased nearly 53 million kWh, which covered 18% of the airports total electricity demand. It was also listed in the 2014 top 30 Local Government List, with usage of 87 million kWh covering 30% of total electricity use (US EPA, 2014).

2.5 ENERGY CONSUMPTION MINIMISATION

The previous section focused on supply side options for sustainable energy use. There are also options available on the demand side, which involve reducing demand. Energy consumption minimisation can be achieved via at least three pathways:

- Directly using less energy.
- Reducing use by substituting with alternatives that use less energy.
- Using energy more efficiently.

All the pathways may overlap somewhat, in particular the first two which both come under the umbrella of conservation, and energy initiatives might be able to be described as belonging to more than one pathway, so this is not a precise definition. But it does provide a starting point for a framework to consider available options, for example:

- Direct Reduction
    - Setting air conditioning temperatures slightly higher for cooling and slightly lower for heating. Information campaigns can guide employees on clothing options to assist maintaining comfort levels.
    - Implementing work-from-home schemes for employees.
    - Effective use of sleep or hibernate mode in computers, and stand-by mode in other electrical devices.
- Reduction by Substitution
    - Encouraging the use of bicycles or other self-powered devices around the airport precinct.
    - Encouraging walking.

- Providing less automated walkways.
- Room temperature water bubblers/dispensers instead of chilled water.

Within the context of these two conservation pathways there are many more possible options that could be considered in order to reduce energy consumption. Looking to real-world examples, Vancouver Airport Authority has implemented several initiatives at Vancouver International Airport. Cycling infrastructure has been improved by building a dedicated 1 km cycleway to connect a neighbouring community where some airport employees live to the airport. The airport participates in and promotes the Vancouver bike to work week. And they have a Green Commuter Program, which encourages and rewards employees who use alternative transportation methods to commute to work including public transport, bicycling, walking and carpool arrangements (Vancouver Airport Authority, 2013).

However, it is possible that the greatest advances in minimising energy consumption can be made via the third pathway – energy efficiency. It holds great potential for increasing the sustainability of energy use at an Airport Metropolis.

2.5.1 EFFICIENCY

At its most basic, energy efficiency is increasing the amount of useful output work obtained for an input unit of energy, or providing the same amount of useful output work while using less input energy. There are many and varied opportunities for increasing energy efficiency, but two that research points to as being very relevant to large airports are building and lighting efficiency, and cogeneration.

Building and Lighting Efficiency

Various studies have shown that the options that offer the quickest payback for greatest decrease in emissions are efficiency measures, particularly building efficiency measures such as insulation, and lighting system efficiencies (McKinsey Global Institute, 2007), (The Economist, 2007). A graphical summary of one such study, produced in 2005, is depicted in *Figure 2.10*. The x-axis depicts the projected number of gigatonnes of CO_2 per year in 2030 that could be avoided. The y-axis measures marginal cost, in €/tonne CO_2. Each rectangle represents an abatement measure; those on the left have a negative marginal cost. For example, “Insulation improvements” are estimated to have a marginal cost of -150 €/tonne CO_2 avoided.

This amount represents a saving to a business when factored over the 25 year period of the figure. In other words, those measures with a negative marginal cost have a payback period less than 25 years, and a lower marginal cost correlates with a quicker payback period.

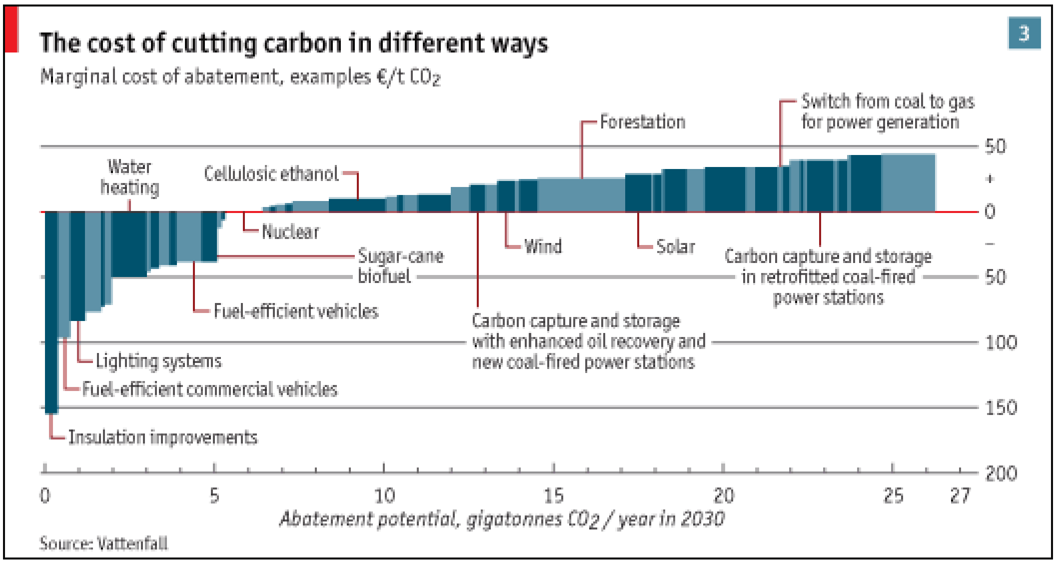

Figure 2.10. Relative costs of CO_2 emission abatement

When lighting alone can account for 40% of an airports electricity consumption (Clean Airport Partnership Inc., 2004), it is apparent that this is a substantial area of focus for efficiency improvements. Numerous examples exist of substantial energy savings at airports by switching to more efficient lighting systems (Siemens, 2007).

Denver International Airport in 2014 commenced a project to replace 5,400 high pressure sodium light bulbs in two parking garages with LED fixtures. These lights are estimated to be 45% more efficient, resulting in net savings of USD $327,000 per year. The cost of the program is $2.7 million, which equates to a 9 year approximate payback period. Over the 20 year estimated lifespan of the new system the electricity savings are projected to amount to $6.5 million (Denver International Airport, 2014).

HVAC systems can also account for around 40% of an airport’s electricity consumption (Clean Airport Partnership Inc., 2004), so general building efficiency improvements are also very important. Building design elements such as passive solar heating, light-coloured roofing, green roofs (such as the main terminal at

Schiphol Airport, Amsterdam), natural ventilation, and passive lighting can be used for airport buildings.

Melbourne Airport has painted the roofs of its T2 and T3 terminal buildings with an advanced technology highly-reflective acrylic paint. This has resulted in a 30% reduction in cooling costs (Melbourne Airport, 2014). These materials are designed to have both high solar reflectivity to prevent heat gain from solar irradiation, but also high thermal emittance to allow heat inside the building to be relatively easily transferred to the outside of the building. These materials work well in climates where the cooling demand over the course of a typical year is higher than the heating demand, because while they are more efficient for cooling applications, they result in a small increase in heating demand during the cooler months.

Green roofs may also contribute to a lessening of the urban heat island effect (Heat Island Group Berkeley Lab, 2007). The Chicago Department of Aviation has developed a Sustainable Airport Manual which is used as a mechanism to lock sustainability requirements into contracts related to the design and construction of projects at O'Hare and Midway Airports (both located in Chicago).

The manual "encourages the installation of vegetated roofs on airport facilities wherever possible to reduce the urban heat island effect, conserve energy, and reduce storm water runoff" (Chicago Department of Aviation, 2012). The two airports now have over 31,000 m2 of vegetated roofs. The largest, accounting for approximately half the total area, is located on the FedEx cargo relocation facility, and is depicted in *Figure 2.11*.

Figure 2.11. Vegetated roof at Chicago O'Hare airport

Other notable green roofs at major airports include 54,000 m^2 on top of the T4 terminal parking complex at Barajas Airport, Madrid. Frankfurt airport first installed a green roof in 1990. Since then, numerous other green roofs have been installed, increasing the total area covered to 40,000 m^2 (Velazquez, 2008)

There are many parameters and components of a HVAC system, and other building energy systems, that can be modified or replaced to increase efficiency. For example, variable frequency drives can replace fixed drives.

Auckland Airport experienced a successful reduction in energy consumption by the HVAC system in the check-in areas of its international terminal building by switching to variable frequency drives. The Energy Management Action Plan notes that the project cost NZD $302, 000 and is achieving monthly savings of 175,000 kWh which equates to a cost saving of NZD $11,000 (Auckland Airport, 2013).

A computerised Energy Management System (EMS) may also provide efficiency gains. In Europe, there is a research project called CASCADE which has the goal of developing ICT solutions for energy efficient airports. It is a project designed for the provision of an ICT solution layer that can sit on top of, and integrate with, existing building energy management systems and provide a framework and methodology for increasing energy efficiency gains by using Fault

Detection and Diagnosis (FDD) algorithms. The information gathered is used to form action plans based around ISO 50001 standards (Blanes, Costa, & Keane, 2013).

The software has been installed for pilot testing at two Italian airports, Rome Fiumicino and Milan Malpensa. While it is still too early to judge the effectiveness of the software in terms of reducing energy consumption, there has already been a significant step at Fiumicino airport with a fault detected by identifying an anomaly in the data where actual air outlet temperature from an air handling unit cooler was significantly higher than that forecast by CASCADE's modelling component (Cascade, 2014).

A "green" IT data centre has been constructed at San Francisco International Airport. The primary source of cooling for the centre is the outside ambient air. The data centre building design incorporates half-dome aisles in the roof where hot air is discharged by efficient exhaust fans, and walls are comprised of floor to ceiling louvres (San Francisco International Airport, 2011).

Cogeneration

At airports, the contemporaneous and high demand for both power and heat makes cogeneration a viable solution for energy saving. In zones closer to the Equator, trigeneration (combined heat, power and cooling) systems can lead to even better results (Cardona, Piacentino, & Cardona, 2006).

This technology falls under the heading of efficiency as it leads to a greater utilisation of input energy. These systems, where electricity is generated onsite, and by-product heat is harnessed, are able to achieve from 60% to 90% efficiency, compared with traditional centralised power generator systems, which achieve around 30% to 40% efficiency (United States Combined Heat & Power Association, 2007).

There are two main reasons for the increased efficiency. Firstly, distributed generation does not require the transmission and distribution of centralised generation and therefore avoids the inherent losses in this component of the system. And secondly, utilising the by-product heat means that more of the total available energy is utilised.

Cogeneration is already in use at many airports, with some of the notable installations being: (Carter & Burgess, 2002):

- 100 MW plant at JFK International Airport (see *Figure 2.12*)
- 50 MW plant at Heathrow Airport
- 90 MW plant at Toronto Pearson International Airport

Figure 2.12. Cogeneration plant at JFK Airport.

Often, cogeneration systems are powered by natural gas, but other options include the harnessing of solar thermal energy and biomass combustion as the source powering the heat engine. Therefore cogeneration systems have great potential for reducing overall energy consumption, and also potentially increasing the utilisation of renewable energy sources.

Distributed generation has another advantage, namely it confers on airport operators an increase in their energy security, simply because the onsite generation is more directly under their control and less susceptible to issues of loss of supply that can affect centralised systems.

Looking specifically at trigeneration, the harnessed by-product heat is applied to both heating and cooling loads, via chillers such as absorption chillers that are powered by a heat source instead of an electric source.

Studies have demonstrated the cost and environmental benefits that can be gained by trigeneration systems, particularly in warmer climatic zones closer to the equator (Cardona, Piacentino, & Cardona, 2006). In these climates, both the heating demand during winter and the cooling demand during summer can be fed from the by-product heat of the system.

The combined heating and cooling load is referred to as the aggregate thermal demand (ATD), and it is often shown to be a reasonably consistent load across an entire year (Cardona, Piacentino, & Cardona, 2006). If such a regular profile does exist in a location, it increases the feasibility of the overall system and maximises the return on capital investment.

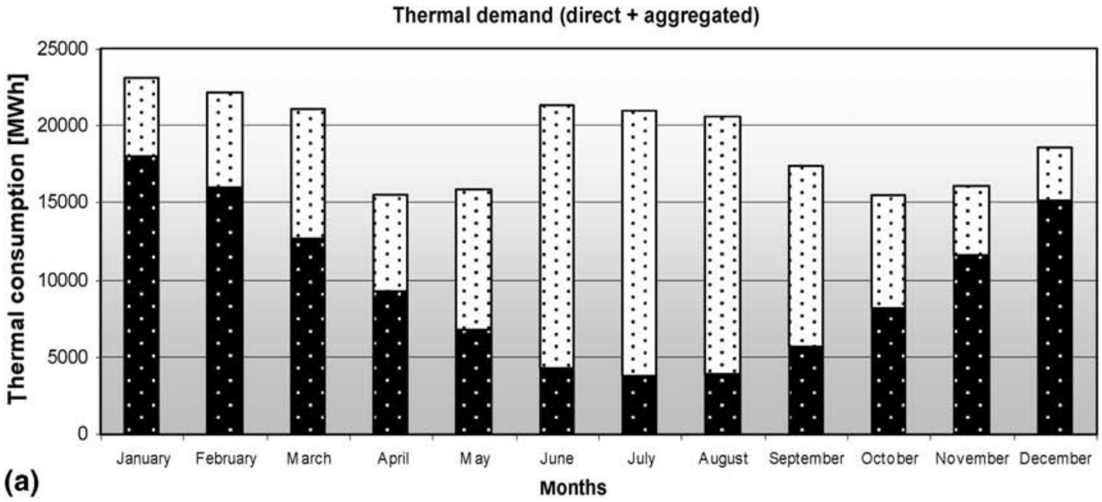

Figure 2.13. Example of aggregate thermal demand for 3 Italian airports.

A particular example from (Cardona, Piacentino, & Cardona, 2006) is shown in **Error! Reference source not found.** and represents a total load across three Italian airports:

- Malpensa, Milan – 26 million passengers in 2003
- Fiumicino, Rome – 27 million passengers in 2003
- Falcone and Borsellino, Palermo – 3 million passenger in 2003

It was also demonstrated in this study that the average power to heat ratios of building demand in airports is close to the typical values for engines used in distributed generation systems.

Therefore, from an energy performance point of view, trigeneration systems are shown to be very effective for the airport sector. In order to determine whether the systems are also economical, it is necessary to conduct an analysis of fuel and electricity prices as well as factoring in emissions.

A detailed case study at Milan airport for such analysis was conducted in the Part II Cardona paper (Cardona, Sannino, Piacentino, & Cardona, 2006). This paper defines a methodology for conducting such analysis, and also a method for optimising the variables of the trigeneration system in order to maximise efficiency. This work is therefore reusable at other airports conducting feasibility studies into trigeneration.

In brief, the methodology consists of the following steps:

1. Analyse the current energy demand and create a number of forecast scenarios related to future energy demand.
2. Understand the performance characteristics of the proposed system (which may be a new system or an enhancement to an existing one), including the gas turbines, the heat recovery boilers, auxiliary boilers, and absorption chillers.
3. Optimise the plant operation by applying linear optimisation programming techniques to the identified constraints, variables and goals of the system for each of the forecast scenarios.
4. Conduct a sensitivity analysis on the future forecast scenarios.

The Milan airport case study was informative because it demonstrated that overall profit could be maximised by maximising the plant running times. However this resulted in an excess of waste heat that could not be harnessed and utilised. When optimising for both profit and a reduction in greenhouse gas emissions, it was shown that the plant should not be run during various off-peak times, foregoing some revenue from the sale of electricity back to the grid.

Therefore the selection of sustainability indicators is an important component of increasing sustainable energy use. These will be investigated in further detail later in this chapter.

Reference was made earlier to the biomass fuelled power plant at Heathrow airport, London. This is actually a trigeneration power plant using an organic rankine cycle power generator. This is a good way to combine one form of renewable energy supply (biomass fuel) with an energy efficiency option (trigeneration). The electric power capacity of the system is 1862 kW and the thermal power capacity is 7851 kW. The thermal power is used 75% for heating applications and 25% for cooling.

Increasingly, airports around the world are adopting trigeneration technology. Rome’s main airport – the Leonardo da Vinci Airport in Fiumicino has a 25.5 MWe and 15 MWt plant fuelled by natural gas. It cost €22 million, but has capacity to meet 90% of the airports electrical and thermal energy requirements (Aeroporti di Roma, 2010).

In Australia, the country's two largest airports at Sydney and Melbourne are both implementing trigeneration systems. The Melbourne plant will have a capacity of 8MW and is due for completion in late 2014. At Sydney, an 8MW system is already completed within the Qantas headquarters on the airport grounds, and a further 4 MW system is planned for the Terminal 3 building.

Other work in this area has led to the development of a generalised performance indicator for assessing the energy saving performance of trigeneration alternatives (Chicco & Mancarella, 2007). The researchers named it the trigeneration primary energy saving (TPES) indicator. This is important work as the results are of direct use to authorities looking to establish financial incentives for the adoption of such technologies. Obviously, in the presence of such incentives, the appeal to airport operators of embracing trigeneration is heightened.

2.6 SUSTAINABILITY INDICATORS

Worldwide, it has become common practice for airports that are innovators in sustainable energy use to adopt a methodology around forecasting, targeting, measuring and reporting that incorporates the following components (Atlanta International Airport, 2012), (Heathrow Airport Limited, 2011), (Hong Kong International Airport, 2013), (Greater Toronto Airports Authority, 2013):

- Select a set of sustainability indicators against which the airport will analyse and report its energy use.
- Ensure systems and processes are in place that allows the accurate measurement of energy use, and other metrics required for those indicators (e.g. PAX per annum).
- Obtain a starting point by capturing measurements for an initial period of time, e.g. one year. This is the baseline.
- Establish forecasts and targets/goals for future energy use. These are expressed in terms of the chosen indicators, and can use the baseline as a reference point.

- Track actual progress through time against the targets, and publish reports.

In addition to their usefulness in analysing progress within an individual airport, sustainability indicators are also important for making comparisons between different airports. Which airports are more sustainable? Which have made the most progress in the previous 5 years? Carefully selected indicators can ensure an “apples versus apples” comparison.

Precisely what should be measured, in an airport context, has been the subject of previous research. (Upham & Mills, 2005) provided a proposed set of environmental sustainability indicators. From their list of 10 indicators related to overall sustainability at airports, items 3 and 4 relate to energy use. They are listed in Table 2.1.

This research was restricted to environmental indicators, and as such did not include in its scope economic or social indicators.

Table 2.1

Energy use environmental indicators suggested by Upham and Mills

Indicator	Absolute measure	Threshold-related measure
3. Static power consumption	Fossil-fuelled electricity consumption, kWh (monthly, yearly) Fossil-fuelled gas consumption, kWh (monthly, yearly) Wind, solar or bio-generated electricity consumption, kWh (monthly, yearly)	Consumption relative to any relevant hourly maxim
4. Gaseous pollutant emissions (from surface vehicles, static power, aircraft)	NO_x, CO_2, N_2O, CO, MNVOC and PM_{10} per source ambient concentrations	Ambient concentrations relative to statutory EU limits

One important point that was made in this study is that absolute indicators are preferred, or at least should be part of the mix, so that environmental impacts are not masked by an increase in passenger or freight movements, as they would be if using indicators normalised to such metrics.

The Global Reporting Initiative (GRI) is another source of potential indicators. GRI provides a complete framework for reporting on sustainability. It is designed to be generic enough to be suitable for any organisation. The current version, G4, contains a number of indicators related to energy use. Summaries of these are listed in Table 2.2

Table 2.2

GRI G4 energy use indicators

Indicator	Description
G4-EN3	Energy consumption within the organization
	Total fuel consumed by both renewable and non-renewable sources in joules
	Total consumption in the four categories of electricity, heating, cooling and steam in joules or watt-hours
	Total sold in the same four categories in joules or watt-hours
	Total energy consumption in joules or watt-hours
G4-EN4	Energy consumption outside of the organization
	Total energy consumed outside of the organization, in joules or multiples
G4-EN5	Energy intensity
	Report the energy intensity ratio. Also report the organisation-specific metric (the ratio denominator) chosen to calculate the ratio
	Report by the same four categories of electricity, heating, cooling and steam
G4-EN6	Reduction of energy consumption
	Report the reduction in energy consumption as a direct result of conservation or efficiency measures, by the four categories, and by reference to an established baseline
G4-EN7	Reductions in energy requirements of products and services
	Report the reduction in energy requirements of any sold products or services, with reference to an established baseline

(source:https://g4.globalreporting.org/specific-standard-disclosures/environmental/energy/Pages /default.aspx)

EN3 and EN4 are absolute indicators, while EN5 is a normalised indicator. The airport can choose its own organisation-specific metric. EN6 and EN7 capture improvements made as a result of energy conservation and efficiency measures.

In terms of using GRI in the airport context, the GRI organisation itself established a process to provide specific guidelines for airport operators. Initially, a report was published titled “A Snapshot of Sustainability Reporting in the Airports Sector” (GRI, 2009). This is a summary of background research conducted into what various airports were doing with sustainability reporting circa 2008. By conducting a desktop search, it found 7 airports that were publishing GRI reports. By analysing what these, along with another sample of 12 airports who were doing non-GRI, were reporting, and how this mapped against the indicators available at the time, a gap analysis was able to inform the creation of the GRI Airports Operators Sector Supplement. For airport operators who wish to publish GRI reports, the AOSS provides detailed airport specific guidance. No new energy indicators are added, but further explanation is given around using the standard GRI indicators outlined above. (GRI, 2011).

Table 2.3 presents a sample of indicators being used by some major international airports. These are taken from published sustainability and environmental reports.

Table 2.3

Sample of real-world airports sustainable energy use indicators

Indicator	Value
Atlanta - 2011 Annual Sustainability Report	
Energy Usage	1,093,107 mmBtu
Energy Usage per square foot	150,496 BTU/sf
(Target)	(Reduce 2008 per sf energy total by 20% by 2020)
Electricity Usage	292,236,544 kWh
Diesel consumption	100,357 gallons
Natural Gas consumption	60,856 mmBTU
Jet Fuel consumption	24,140 gallons
Automotive Fuel consumption	145,499 gallons
GHG Emissions	1,300,525 Tons
GHG Emissions per Passenger	0.015 Pounds/Passenger
(Target)	(Reduce 2008 per passenger GHG emissions by 20% by 2020)
Linked to GRI?	Yes
Heathrow - 2010 Sustainability performance summary	
Total Energy Usage	894 GWh
CO_2 emissions from energy use	320,000 Tons
(Target)	(Reduce 2010 levels by 1% by 2011)
Total CO_2e emissions	2,238,000 Tons
Linked to GRI?	No
Hong Kong - Sustainability Report 2012/13	

Absolute GHG emissions	174,833 Tons CO_{2e}
Intensity-based GHG emissions	1.81 $kgCO_2e$/WLU (1 WLU = 1 passenger or 100kg cargo)
(Target)	(Reduce 2008 level by 25% by 2015)
Electricity consumption per passenger	4.87 kWh per passenger
Electricity consumption	278,600 kWh
Diesel consumption	851,600 Litres
Petrol consumption	78,100 Litres
LPG consumption	5,150 Litres
Linked to GRI?	Yes
Toronto Pearson - GTAA corporate responsibility report 2012	
Natural gas consumption	1,305,484 gigajoules
Unleaded fuel consumption	566,197 litres
Diesel fuel consumption	704,722 litres
Electricity consumption	277,544 MWh
Energy saved due to conservation and efficiency improvements	12,655 gigajoules
Total direct and indirect greenhouse gas emissions	74,008 CO_2e Tonnes
Linked to GRI?	Yes

References: (Atlanta International Airport, 2012), (Heathrow Airport Limited, 2011), (Hong Kong International Airport, 2013), (Greater Toronto Airports Authority, 2013)

ISO 50001 is an international standard for Energy Management Systems. It provides a framework for organisations large and small, including airports, to establish systems and processes to improve energy performance. It is based on a Plan-Do-Check-Act continual improvement process.

Adopting the requirements outlined in the standard could assist airports to formally introduce energy policies, targets, and action plans. The approach is summarised as:

- Plan: conduct the energy review and establish the baseline, energy performance indicators (EnPIs), objectives, targets and action plans necessary to deliver results in accordance with opportunities to improve energy performance and the organization's energy policy.
- Do: implement the energy management action plans.
- Check: monitor and measure processes and the key characteristics of its operations that determine energy performance against the energy policy and objectives and report the results.
- Act: take actions to continually improve energy performance and the Energy Management System

(ISO, 2011)

The following is a non-exhaustive list of some airport-controlling organisations that have achieved ISO 50001:2011 certification:

- Brussels Airport Company
- SEA – Malpensa and Linate Airports
- GMR Hyderabad International Airport Ltd
- SAGAT – Turin Airport

2.7 DECISION SUPPORT AND OPTIMISATION

This section reviews decision support methods and tools that might be suitable in the airport sustainable energy context. Two important areas where decision support is valuable are project selection and managing ongoing operations. Selection methods and tools can help decide which sustainable energy initiatives should be chosen for implementation. In the operations phase, decision support methods and tools can help maximise the level of sustainability achieved.

The aim of decision support methods is to optimise decision making. A decision support framework helps to guide decision makers through a structured process to give the best chance of achieving this goal.

2.7.1 DECISION SUPPORT FRAMEWORKS

The first framework reviewed is the Integrated Sustainability Decision-Support Framework (Azapagic & Perdan, 2005). Its components are grouped into three high-level steps – problem structuring, problem analysis and problem resolution. The steps are revisited iteratively throughout the decision making process until a final decision is reached. A flow chart representing the components of the framework is shown in *Figure 2.14*.

Typically, decision making in the sustainable energy context will involve attempting to minimise or maximise (optimise) a number of different indicators. For example, minimise CO_2 emissions, maximise total kWh generated from RET, and minimise cost. In response, the framework specifies the use of a Multiple Criteria Decision Analysis (MCDA) technique, such as Goal Programming.

Another relevant framework is the Sustainable Business Transformation Roadmap (Ahmed & Sundaram, 2012). The term roadmap is used to describe the high-level process, similar to the three steps described in the previous example; however this framework incorporates five steps (see *Figure 2.15*). The roadmap encompasses a cyclic journey where the airport goes from an initial learning phase through to implementing an initiative, and then repeating the whole process again in a cycle of continuous improvement.

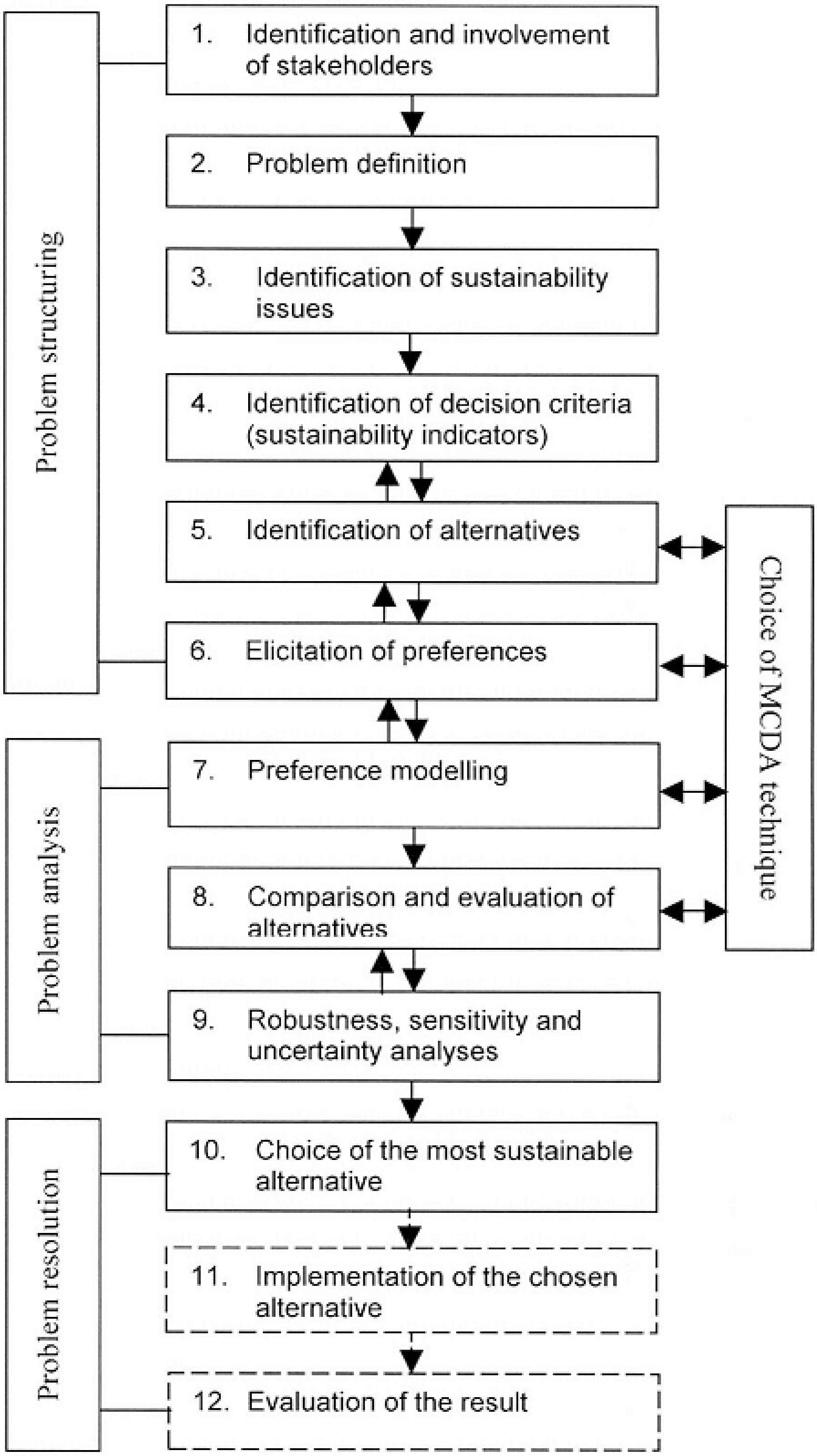

Figure 2.14. Integrated Sustainability Decision-Support Framework (Azapagic & Perdan, 2005).

Figure 2.15. Sustainable Business Transformation Roadmap (Ahmed & Sundaram, 2012)

An airport-specific evaluation decision support framework has also been proposed (Fann & Rakas, 2011), which breaks an airport down into 5 functional areas (airfield, ground support equipment, terminal facilities, ground transportation and general planning) and, against these areas, cross references environmental impact categories, such as global warming. More detailed effort is then made in the matched cross reference intersections to identify specific objectives and criteria. The framework also includes the use of a number of different MCAD techniques depending on the complexity and nature of the alternatives.

Looking across all three of these frameworks, some common elements can be seen:

- Stakeholder engagement
- Nominating a sustainability champion
- Knowledge acquisition/learning phase
- Pre-feasibility assessment to select a number of alternatives
- Identification of suitable sustainability indicators
- Formalised assessment of alternatives via an MCDA approach
- Decision implementation
- Cycle iteration

The next sections will focus on specific tools and techniques that can assist in applying these steps, in particular knowledge acquisition, pre-feasibility assessment, and decision analysis via MCDA.

2.7.2 KNOWLEDGE BASES

A knowledge base is useful in the early stages of decision making. This is the learning phase. Knowledge bases guide decision makers in quickly acquiring information in relevant areas. Sometimes real-life case studies can be a beneficial component of the knowledge base.

An example of an extensive airport-specific sustainability knowledge base is the Chicago Department of Aviation Sustainable Airport Manual. Within the general sustainability scope of this document is good coverage of energy sustainability topics. The information is broken down into three phases – planning, design and construction, and operations and maintenance (Chicago Department of Aviation, 2013)

Each topic contains details on what is required to achieve sustainability outcomes in each area, instructions on how it might be implemented, best practice guidance, and also case studies highlighting real-world scenarios.

By utilising an existing knowledge framework, an airport that has limited practical experience in implementing sustainable energy initiatives can gain a deeper level of understanding and be guided towards optimal selection choices for their specific operating environment.

Another knowledge base tool is the Airport Sustainability Assessment Tool, which is an Excel-based package, built by the Transportation Research Board. Although it is directed at sustainability issues generally, it does have content specific to energy options. It uses a series of interactive questions to guide the user towards further information, based on their current level of familiarity and planning around sustainability options.

For users just starting out, it provides case-study information about real-world airport projects already undertaken. And it allows users to focus on a subset of areas that might be of interest to them based on responses to the questions.

For more advanced users who already have specific sustainable energy options in mind, the tool provides quick links into its knowledge base which has more detailed information about those options tailored to the airport setting. It is a free tool, and available for download (Transportation Research Board, 2014).

2.7.3 SELECTION AND FEASIBILITY ASSESSMENT

RETScreen is a software package developed by Natural Resources Canada, an agency of the Canadian Federal Government. It is available free of charge and can be downloaded from www.retscreen.net. In addition to the software package itself, there is also a complete set of training materials available and a knowledge base and support area.

The software is structured within the Microsoft Excel format. It is described as "pre-feasibility" modelling software. It allows users to model various sustainable energy scenarios and perform calculations on items such as the expected energy output from an energy generation design, energy savings from an efficiency measure, greenhouse gas savings, and financial pay-back analysis.

It provides a number of project types, e.g. Solar PV, Solar hot water and wind turbines. For each of the project types it has an extensive product database. The details of real-world products are listed which enables the calculations to be accurate in terms of expected energy output/savings and cost.

RETScreen also has a weather database built-in. This data is collected from NASA and a number of other sources. It has wind, irradiation, temperature and other data for many locations world-wide.

It is described as pre-feasibility software because it assists decision makers to conduct initial analysis into possible projects. Enough detail can be entered into the software so that reasonably accurate results are produced. This allows superior options to be identified relatively quickly and cheaply, and shortlisted for more detailed analysis.

The RETScreen software suite also includes another tool, RETScreen Plus. This is a performance analysis module which is designed for use after a sustainable energy project is completed to monitor its ongoing operation. It has the capability to update its weather database on a near real-time basis so that actual performance can be compared against forecasts.

It can also be used for targeting and reporting, with features that support standard and customisable reports, analytics such as time-series graphs, and export to a variety of formats, including pdf and csv, for presentation of results or integration with other systems.

It has features that support the three important operational activities of data collection, analysis and reporting. Airports can use it to enter their baseline data, their targets and their ongoing performance measurements. The software will track performance against targets and has a variety of visualization features for reporting on the progress.

In terms of analysis, the software can be used not only for tracking the actual performance against the expected performance, but also for identifying factors of influence between drivers (e.g. number of cooling degree days) and energy production or consumption (e.g. performance of an air conditioning system) using regression analysis.

2.7.4 DECISION ANALYSIS

A number of tools exist to implement MCDA decision analytics. One that meets the criteria of being freely available open-source software is Decision Deck-diviz. It is built on an open XML web-services-based architecture and can be downloaded from www.decision-deck.org.

This tool can be used in stand-alone form as a desktop application, but there is also the possibility of exposing its features as a service-based API which would be ideal if, for example, the functionality was to be integrated with a decision support system. This is possible because of the XMCDA standard, also produced by Decision Deck, which allows interoperability of MCDA components.

Diviz is a good choice for decision analysis because it doesn't enforce any particular decision algorithm. It provides a workflow canvas on which inputs can be connected with a wide choice of algorithms that have been implemented.

2.8 SUMMARY AND IMPLICATIONS

This section reviews the information presented in this chapter. Summary tables are provided from each area of investigation that list priority areas for further consideration.

After assessing the information presented on RET's, it is proposed that there are a number that are suitable for broad scale adoption at Airport Metropolises around the world. Some, like solar PV, have already been proven successful in many installations. Others, like biomass and geothermal are increasingly being used. While others, such as wind, appear to be overcoming early adoption hurdles and will likely become popular in the future.

Table 2.4
RET Priority areas

RET
Solar PV
Solar Thermal
Biomass
Geothermal
Wind

The energy consumption minimisation section reported on a few key areas that account for a large proportion of energy costs at airports, namely building and lighting energy requirements.

Table 2.5
Energy Efficiency Priority areas

Energy Efficiency Measure
Lighting
Buildings
Cogeneration and Trigeneration

The discussion on sustainability indicators focused on the set of indicators from the GRI framework. These would appear to be the best choice for airports wanting to adopt globally recognised best practice in this area.

Table 2.6
Reporting Indicators Priority Areas

Reporting Framework
Global Reporting Initiative (GRI) v4

In terms of sustainable energy use standards compliance, current world's best practice is to attain ISO 50001 certification.

Table 2.7

Standards Compliance Priority Areas

Standards Framework
ISO 50001

Topics related to decision optimisation were reviewed. Initially overarching frameworks were investigated, followed by investigation into various tools from the common and relevant elements of the frameworks that are candidates for inclusion in the resource kit.

Table 2.8

Decision Optimisation Priority Areas

Element	Priority area
Knowledge Bases	Chicago Department of Aviation Sustainable Airport Manual
Feasibility/Selection Tool	RETScreen
Decision Analysis Tool	Decision Deck-diviz

This concludes the background research and literature review. In the next section, the items listed above in the summary tables as priority areas will be incorporated into the decision support framework and resource kit.

Chapter 3: Research Design

3.1 METHODOLOGY AND RESEARCH DESIGN

The aim of this research is to investigate sustainable energy options for Airport Metropolises and develop an innovative decision support framework and resource kit that can assist decision makers to adopt the optimal sustainable energy options for their airport.

Figure 3.1 lists the fundamental steps of the research method undertaken to achieve this research objective. This provides an overview of the research design and methodology.

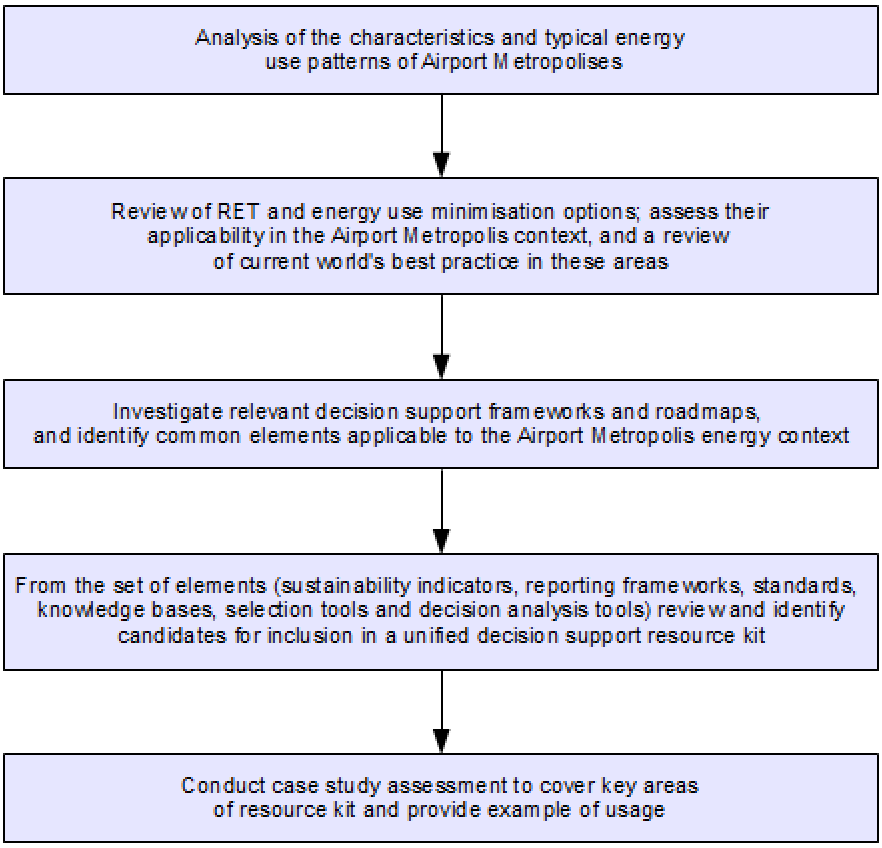

*Figure 3.1.*Steps of the research process

The first three steps were the subject of the initial phase of the background literature review. At this point, further areas for investigation were identified, namely sustainability indicators, reporting frameworks, standards, knowledge bases, selection tools and decision analysis tools. These form the basis of the fourth step which was then addressed through-out the remainder of Chapter 2.

In the Chapter 2 summary, items for inclusion in the decision support framework were proposed, as were specific tools for the resource kit. During the investigation, consideration was given to whether tools were openly accessible and available, and their suitability to being integrated into other systems, for example, a decision support system. The final design selections are summarised in *Figure 3.2*.

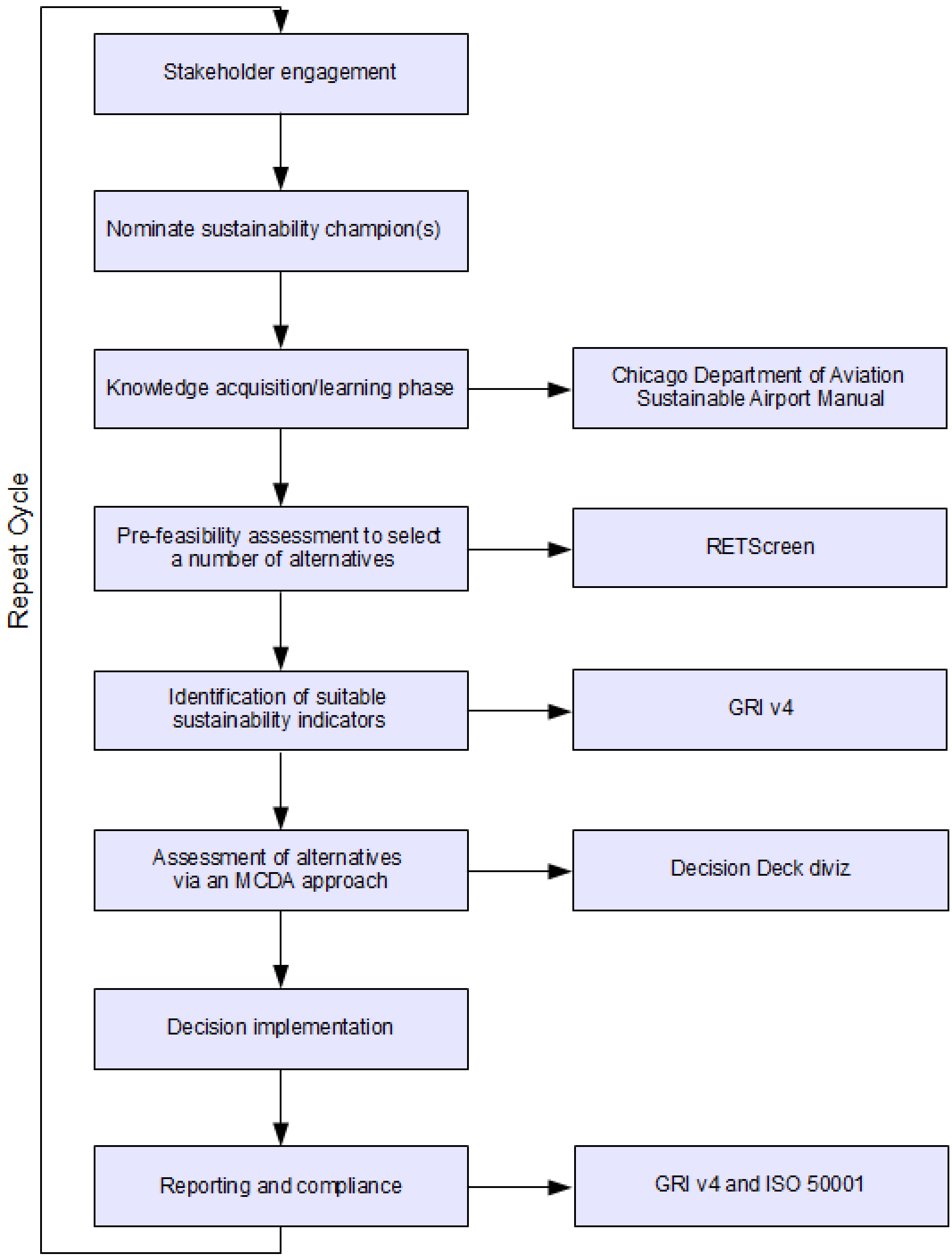

Figure 3.2. Decision support framework and resource kit

The flow from top to bottom on the left-hand side of *Figure 3.2* is the decision support framework. The tools linked across on the right-hand side form the resource kit. Having brought these items together, the last step of the methodology specifies that case study assessment of key areas of the framework and resource kit will be conducted, to test their suitability, and to provide examples of usage.

The design of the case studies has been based on the following factors:

- In terms of tools, to focus on the key software packages that have been identified, namely RETScreen for selection and pre-feasibility assessment, and Decision Deck-diviz for decision analysis.
- In terms of RET, to focus on the areas of solar PV and wind energy. The weather data for these types of renewable energy systems is freely available, and it is also reasonably straight forward to design hypothetical scenarios that can fit within this scope. This ensures that a technology that is already widely adopted is covered (Solar PV), as is a technology that is just starting to be used in the Airport Metropolis context (Wind).
- Using Brisbane Airport. This research has been conducted in Brisbane, so it is an obvious choice to use Brisbane Airport as the focus where possible. It also fits the definition of an emerging Airport Metropolis. In recent years, shopping centres, hotels, office, retail and leisure facilities have all either been constructed or are in planning phases. Also, Brisbane Airport is a partner in the Airport Metropolis research project.

3.1.1 CASE STUDY DESIGN

What follows is a brief description of the design of five case studies.

Case Study 1 – Solar PV Rooftop at BNE – manual calculations

A major solar installation on a large building at Brisbane Airport is proposed. The building chosen is the DFO shopping centre building. The following method is used to determine what the resulting output would be for a hypothetical system design:

1. Calculate area
2. Calculate energy input
3. Calculate energy output
4. Apply Reduction factors

Case Study 2 – Solar PV Rooftop at BNE – RETScreen calculations

The parameters of this case study are the same as those in the first case study. However the execution is done with the RETScreen software package instead of manually. This includes utilising the product and weather data repositories that it is bundled with.

The reason for doing this is to compare and contrast the respective results obtained. This goes towards validating the effectiveness of the tool.

Case Study 3 – Wind Turbine at BNE – manual calculations

In this case study a hypothetical wind turbine is proposed. Wind data from the Australian Bureau of Meteorology is used and calculations derive the energy output that could be expected from an installation onsite at Brisbane Airport.

The inspiration for this case study comes from the observation that some airports around the world are beginning to embrace wind power. This implies that the problems around radar interference are being overcome.

In addition, the wind case study, just like the PV case study, can be performed twice, once manually and once with RETScreen.

Case Study 4 – Wind Turbine at BNE – RETScreen calculations

The same parameters as used in case study 3 are plugged into the RETScreen software package, again to enable analysis of the similarities and/or differences with the manual results.

Case Study 5 – Decision analysis of Solar PV and Wind alternatives with Decision Desk-diviz

In this section, two scenarios are examined via decision analysis. Following on from the earlier case studies, the first scenario takes findings from the RETScreen calculations of both the Solar PV and Wind scenarios and evaluates them as alternatives using the Decision Desk-diviz decision analysis tool in order to select the optimal choice based on some example decision criteria. This scenario is hypothetical and is used to demonstrate the process and capabilities of this approach.

The second scenario takes another hypothetical rooftop solar PV project and uses it as a baseline to conduct a sensitivity analysis. Accurate estimates of project cost and real-world data such as current and forecasted electricity grid supply costs are used and a number of variations to the baseline are evaluated through Decision Desk-diviz to highlight which variations most significantly affect the decision outcome..

3.2 SUMMARY

The case study results are presented next in Chapter 4. An analysis of the results follows in Chapter 5. And then conclusions are presented in Chapter 6.

Chapter 4: Results

4.1 INTRODUCTION

This chapter contains the details of the five case studies that were previously identified and summarised in chapter 3.

4.2 CASE STUDIES

4.2.1 CASE STUDY 1 – SOLAR PV ROOFTOP AT BNE – MANUAL CALCULATIONS

In this case study, a major solar installation on a large building at Brisbane Airport is proposed. The building chosen is the DFO shopping centre building. The following method is used to determine what the resulting output would be for a hypothetical system design:

1. Calculate area
2. Calculate energy input
3. Calculate energy output
4. Apply Reduction factors

Calculate area

The total space available for solar panels needs to be calculated. Real-world projects need to assess roof-top conditions of proposed buildings as there will be a variety of plant, equipment and so on located on the roofs of typical airport buildings.

The total area of the DFO building was calculated using a small prototype web-based application that integrates with Google Maps via the Google Maps API[2], which was custom-developed for this research. The application simply allows the plotting of a shape over a map and returns the total area in square metres. The source code for the application is listed in Appendix A. There are a number of software tools that expand on this concept and provide extensive functionality related specifically to maps-integrated solar resource estimation. One is PVWatts, a free

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[2] Application Programming Interface

web-based tool produced by NREL (National Renewable Energy Laboratory), and available at http://pvwatts.nrel.gov/.

Figure 4.1 demonstrates the application in use, targeting the DFO building:

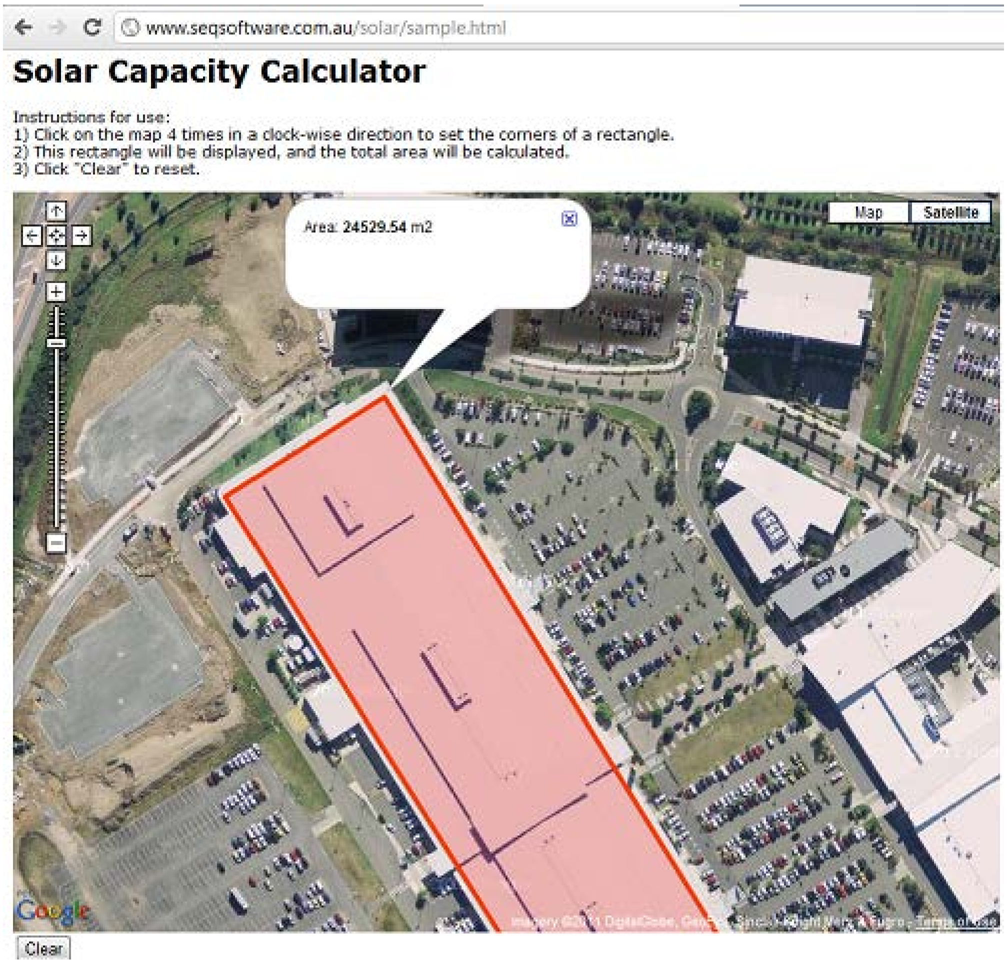


Figure 4.1. User interface for roof-top area plug-in to Google Maps.

The DFO roof area is approximately 25,000 m^2. A detailed assessment of the roof would be required in order to determine what percentage of the total roof area is available to be covered with solar panels. Panels can only be installed in vacant areas, and in addition they cannot totally fill those available areas as space needs to be kept free for operational support and maintenance access. For the purposes of this case study, a conservative estimate of 50% of total roof area is used. This means that it will be assumed that 12,500 m^2 of solar panels will be installed.

Calculate energy input

The amount of energy available to the solar panels depends on the location and the installation type. The following figures are for different installation types, all for the location of Brisbane, Australia (Lat 27°25′ S, Long 153°05′ E). These figures are listed in Table 4.5 of the Australian Solar Radiation Data Handbook (ANZSES, 2006). They are based on meteorological data which is then applied to calculations to obtain the estimated energy input, as a daily mean value.

- Fixed horizontal surface – 4.97 kWh/m^2/day
- Fixed at latitude angle (north facing) – 5.5 kWh/m^2/day
- Tracking on polar axis fixed at latitude angle (north facing) – 6.94 kWh/m^2/day
- 2-axis tracking – 7.16 kWh/m^2/day

The unit of kWh/m^2 that the above values are provided in is sometimes referred to as 1 “peak hour of insolation”, or simply “1 sun”.

It is very convenient to be able to use published data such as this, as the measurements and calculations involved to obtain these figures are very detailed, but the end result of values measured in the unit of peak hours of sun is straight forward to use in calculations to obtain system output.

Each project needs to conduct a cost-benefit analysis to determine the most appropriate installation type. In this case study, for the purposes of calculating solar estimates, it is assumed that the installation type is fixed to a horizontal surface. In other words, the panels are attached to mounting brackets that are fixed directly to the roof (no tilt). This method requires less support structure under the panels, and therefore is possibly the cheapest method. However, in real-world applications it may not be possible if there is a minimum tilt requirement for self-cleaning from rain and to allow run-off.

Fixing at the latitude angle is optimal because the sun's rays at equinox will strike the panels at the most effective perpendicular angle, and then move away towards the horizon at winter solstice and towards the mid-sky at summer solstice, which provides an averaging effect over the course of a whole year. For many residential installations, where roofs are typically pitched, this can sometimes be closely aligned with the latitude angle. For example, in Brisbane the latitude is 27.5 degrees and the typical pitch of house roofs is 22.5 degrees.

In other scenarios, the roof is near horizontal and a cost-benefit analysis is required to contrast the benefit of extra energy available to the panels over the lifetime of the installation, versus the extra up-front capital cost of the substructure required to tilt the panels.

Other factors to consider include shading, which obviously needs to be avoided; the layout of the panels and ensuring access for maintenance and system components, and the option of tracking systems which would also require cost-benefit analysis to determine if the additional input energy harnessed is worth the extra cost outlay.

Calculate Energy Output

The amount of energy produced by the case study system depends on the amount of energy available at input (determined above), the solar panels chosen, and application of reduction factors that account for real-world losses.

Solar panels have a rated power output. For this case study, Suntech STP180S-24 panels have been chosen. The panel is comprised of Mono-crystalline silicon cells, and the dimensions of the panel are 1,580mm × 808mm. The rated power output is[3]:

"Maximum Power at STC (Pmax) 180Wp, where STC: Irradiance 1000W/m^2, Module temperature 25ºC, AM=1.5, Temp co-efficient -0.48 %/ºC"

Given 1 peak sun of input (irradiance 1000W/m^2), each panel will produce approximately 180W, under Standard Test Conditions (STC). For every degree Celsius above or below 25ºC, the panel will produce 0.48% less power.

Given that one panel of size 1,580mm x 808mm will deliver 180W from 1 peak sun, this can be converted to a square metre value, which suits the methodology of this case study of determining the possible power produced for a given roof area. The output per square metre value is:

$$0.18 \div (1.58 \times 0.808) = 141 \text{ W}$$

This figure can be cross-validated by examining the panel conversion efficiency. The Sun-power panels have a rated conversion efficiency of 14.1%. In other words, given 1 peak sun of input energy, the panel will deliver 141W (14.1% of 1,000W). Because 1 peak sun refers to the insolation received on one square

[3] http://www.energymatters.com.au/images/suntech/suntechstp180s24ad.pdf

meter, we would expect this value to be very close to the square metre value that was calculated above.

Therefore, the total energy produced, per day, *in a theoretical environment*, on the roof of the DFO building, by a solar panel array of 12,500 m^2 in total area with panels fixed directly to the horizontal roof is:

$$12500 \times 0.141 \times 4.97 = 8759.62 \text{ kWh}$$
$$(area \times efficiency \times solar\ irradiance)$$

When multiplied by 365, this gives a yearly output of 3,197.26 MWh

Apply Reduction Factors

The amount of energy produced in real-world settings is less than that produced in a theoretical model. There are a number of real-world losses that occur. Some of the important ones are detailed below. For each loss type, an estimate is given for how much the output should be reduced by to account for the loss. These figures are taken from the *PV Grid Connect Systems (Non-UPS) System Design Guidelines* manual produced by the Australian Clean Energy Council (Clean Energy Council, 2004):

a) Temperature de-rating. Solar panels produce their maximum output under ideal conditions, including a certain ambient temperature. For the panels in this case study, that temperature is 25 degrees Celsius. The rating of the panels gives a temperature co-efficient of -0.48 %/ºC. To accurately calculate this loss at a given location, a probability density function is required to determine how often and by how much the temperature at the location deviates from ideal. The Clean Energy Council (CEC) manual recommends an 87.5% reduction factor. (Multiply the theoretical energy output by 0.875 to get the real-world energy output).

b) Dirt. As dirt accumulates on the surface of the solar panels, the amount of energy input reaching the cells decreases. Regular cleaning is essential to minimise these losses. The CEC manual recommends a 95% reduction factor to allow for average losses.

c) Inverter inefficiency. Solar panels produce DC electricity which must be converted to AC for both end-use and re-distribution to the grid. An inverter is used for this and a certain amount of energy is lost during the conversion process. The CEC manual recommends a 90% reduction factor to allow for these losses.

d) Cabling losses. A number of power cables are used in a solar panel array system to connect the panels, inverters, and other sub-components of the system before final delivery to end-use. These cables are also subject to losses. The CEC manual handbook recommends a 95% reduction factor to allow for these losses.

The total product of the reduction factors in this case study is:

$$87.5 \times 95 \times 90 \times 95 = 71\%$$
$$(temp\ derating \times dirt \times inverter\ efficiency \times cabling)$$

Therefore the total annual energy produced by the case study model, in a real-world environment, could be in the vicinity of:

$$3197.26 \times 0.71 = 2270.31 \text{ MWh}$$

4.2.2 CASE STUDY 2 – SOLAR PV ROOFTOP AT BNE – RETSCREEN CALCULATIONS

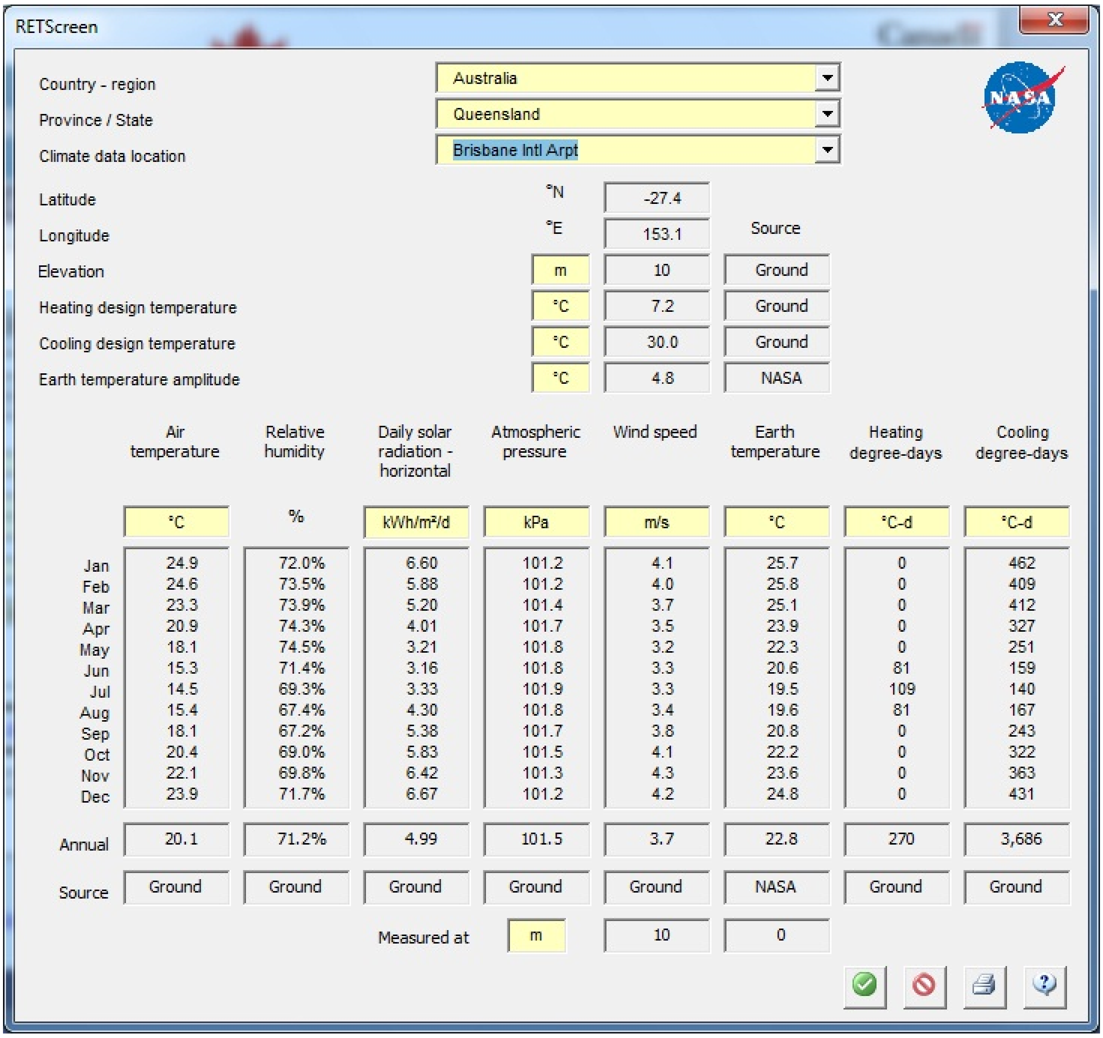
In this case study the same project parameters are used as in the first case study (installation size, location, type), but a different methodology is used. RETScreen is used to process the inputs and calculate the estimate of output energy produced by the system.

The first data entry form in RETScreen is called *Project Information*. The screen shot in *Figure 4.2* illustrates the types of data required for entry, and the actual values entered for this case study:

Figure 4.2. Initial Project Information data entry screen.

In *Figure 4.2*, *Analysis type* simply refers to a RETScreen convention where method 1 is a less detailed analysis and method 2 is more detailed. *Heating value reference* can either be set to *Higher heating value (HHV)* or *Lower heating value (LHV)*. Typically USA and Canadian projects use the former while the latter is used for projects in the rest of the world.

When clicking on the Select climate data location link, the dialog depicted in *Figure 4.3* is presented, allowing selection of the most relevant location:



RETScreen

Country - region		Australia	
Province / State		Queensland	
Climate data location		Brisbane Intl Arpt	
Latitude	°N	-27.4	Source
Longitude	°E	153.1	
Elevation	m	10	Ground
Heating design temperature	°C	7.2	Ground
Cooling design temperature	°C	30.0	Ground
Earth temperature amplitude	°C	4.8	NASA

	Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
Jan	24.9	72.0%	6.60	101.2	4.1	25.7	0	462
Feb	24.6	73.5%	5.88	101.2	4.0	25.8	0	409
Mar	23.3	73.9%	5.20	101.4	3.7	25.1	0	412
Apr	20.9	74.3%	4.01	101.7	3.5	23.9	0	327
May	18.1	74.5%	3.21	101.8	3.2	22.3	0	251
Jun	15.3	71.4%	3.16	101.8	3.3	20.6	81	159
Jul	14.5	69.3%	3.33	101.9	3.3	19.5	109	140
Aug	15.4	67.4%	4.30	101.8	3.4	19.6	81	167
Sep	18.1	67.2%	5.38	101.7	3.8	20.8	0	243
Oct	20.4	69.0%	5.83	101.5	4.1	22.2	0	322
Nov	22.1	69.8%	6.42	101.3	4.3	23.6	0	363
Dec	23.9	71.7%	6.67	101.2	4.2	24.8	0	431
Annual	20.1	71.2%	4.99	101.5	3.7	22.8	270	3,686
Source	Ground	Ground	Ground	Ground	Ground	NASA	Ground	Ground
			Measured at	m	10	0		

Figure 4.3. RETScreen climate data selection dialog.

After entering the *Project Information* details, the *Energy Model* form must be completed. This is where the solar panels are selected from the real-world product database. It is also where real-world losses are entered which go to the setting of a *Capacity Factor*. This is then applied to the theoretical output in order to arrive at a reduced real-world estimate. The following fields are available for data entry:

Table 4.1

Settings for the Photovoltaic project type

Setting	Description
Miscellaneous losses	This is a catch-all for non-inverter related losses, which includes the following as described in Case Study 1: • Dirt (5% loss) • Cabling (5% loss)
Inverter Efficiency	Equivalent to the inverter efficiency factor as described in Case Study 1 (10% loss).
Inverter Capacity	Not applicable for this case study.
Inverter Miscellaneous Losses	Power conditioning losses, e.g., if the project has DC-DC converters or step-up transformers. Also not applicable for this case study.

The screenshots in *Figure 4.4* and *Figure 4.5* illustrate the Energy Model form. Note that the user interface is designed around entry of the number of solar panels that are desired. Because this case study is starting from the point of knowing what area is required to be covered, quick trial and error is performed to determine the number of solar panel units so that data entry into RETScreen can be achieved. The program provides a display of the *Solar collector area* for any given number of units, making it an easy task to determine that 9,765 panels are required for a total area of 12,500 m^2.

RETScreen Energy Model - Power project

Proposed case power system **Increm**

Technology		Photovoltaic
Analysis type		○ Method 1 ⦿ Method 2
Resource assessment		
Solar tracking mode		Fixed
Slope	°	0.0
Azimuth	°	

☑ Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity export rate $/MWh	Electricity exported to grid MWh
January	6.60	6.60		266.7
February	5.88	5.88		215.8
March	5.20	5.20		213.3
April	4.01	4.01		162.5
May	3.21	3.21		137.1
June	3.16	3.16		132.1
July	3.33	3.33		144.0
August	4.30	4.30		183.4
September	5.38	5.38		217.5
October	5.83	5.83		241.0
November	6.42	6.42		254.3
December	6.67	6.67		270.7
Annual	**4.99**	**4.99**	**0.00**	**2,438.5**

Annual solar radiation - horizontal	MWh/m²	1.82
Annual solar radiation - tilted	MWh/m²	1.82

Figure 4.4. Top section of the Energy Model form

Photovoltaic			
Type		mono-Si	
Power capacity	kW	1,757.70	
Manufacturer		Suntech	
Model		mono-Si - STP180S - 24	9765 unit(s)
Efficiency	%	14.1%	
Nominal operating cell temperature	°C	45	
Temperature coefficient	% / °C	0.40%	
Solar collector area	m²	12,501	
Miscellaneous losses	%	10.0%	
Inverter			
Efficiency	%	90.0%	
Capacity	kW		
Miscellaneous losses	%		
Summary			
Capacity factor	%	15.8%	
Electricity exported to grid	MWh	2,438.5	

Figure 4.5. Bottom section of the Energy Model form

The final result, contained in the bottom line *Electricity exported to grid*, is an estimation of 2,438.5 MWh per year produced by the hypothetical system. This compares with the result of 2,270.3 MWh per year from case study 1. The difference being that the result from RETScreen is 7.5% higher than that produced by the manual methodology. Further analysis of these results will be conducted in the next chapter.

4.2.3 CASE STUDY 3 – WIND TURBINE AT BNE – MANUAL CALCULATIONS

For this case study, we assume a hypothetical scenario similar to the wind turbine installation at East Midlands Airport where two turbines were installed, but based at Brisbane Airport. The turbines used at East Midlands were the WTN250 model produced by Wind Technik Nord. These turbines have a hub height of 31.5 metres, with a rotor diameter of 27 metres.

Unfortunately, although the RETScreen product database is extensive, it does not include this model. So for the purposes of this case study, and to allow comparison with the next case study using RETScreen, the Nordex N29 has been selected. It is a model of similar physical dimensions. Its key performance parameters are listed in Table 4.2,

Table 4.2

Key performance parameters of Nordex N29

Hub height	31.5 m
Rotor diameter	29.7 m
Startup speed	3 m/s
Rated speed	15 m/s
Furlong speed	25 m/s

(source: http://en.wind-turbine-models.com/turbines/56-nordex-n-29)

Throughout this case study, guidance for the methodology comes from the book *Renewable and Efficient Electric Power Systems*, by Gilbert M. Masters (Masters, 2004).

An assumption is made that the chosen installation location at the case study airport – BNE – is in an area that fits wind roughness class 1, which is defined as “open areas with a few windbreaks”.

Raw weather data was sourced from the Australian Bureau of Meteorology (BOM). The chart in *Figure 4.6* illustrates 10 years of 3 hourly snapshots of wind speed at Brisbane Airport. The anemometer at this BOM observation station is 10 metres above ground. The station is located at -27.3917, 153.1292.

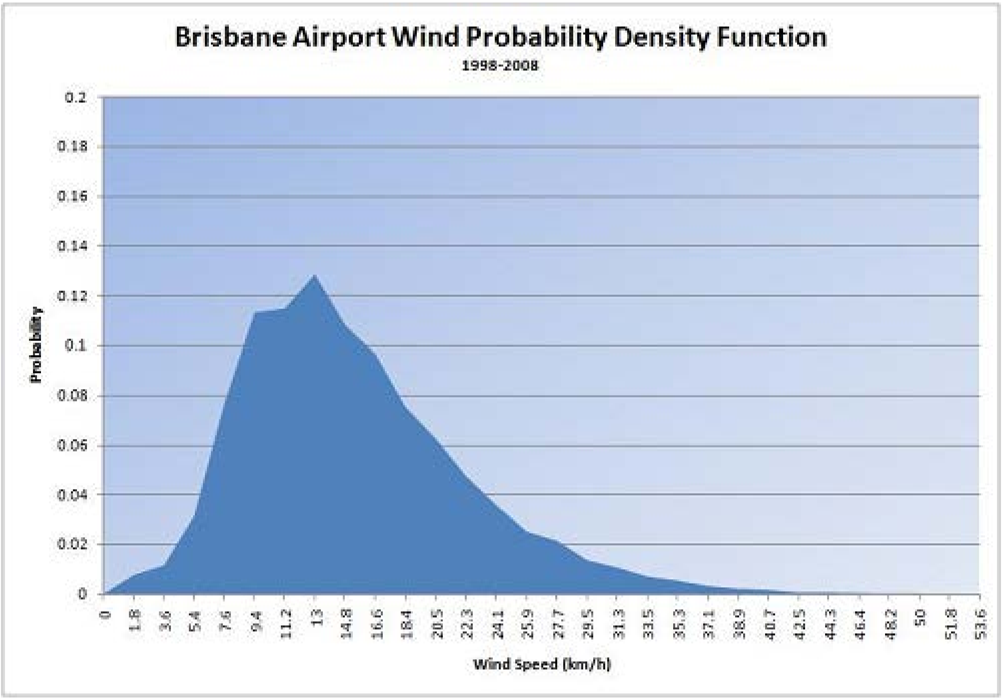


Figure 4.6. Brisbane Airport wind speed data (source: BOM).

The distribution closely resembles the Rayleigh probability density function (p.d.f.), depicted below in *Figure 4.7*.

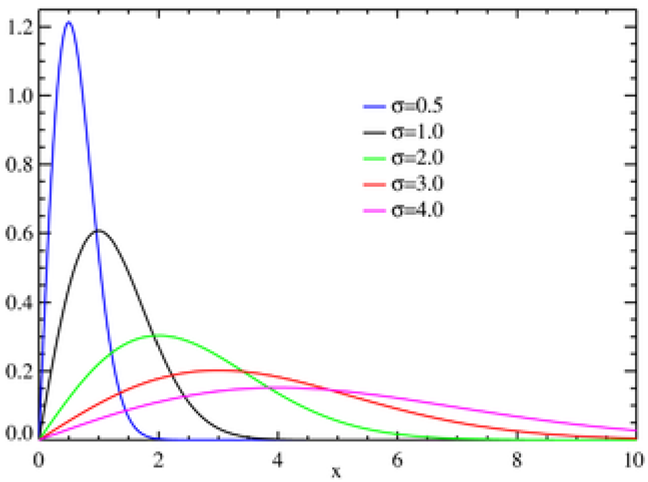


Figure 4.7. Rayleigh probability density function.

(source: http://en.wikipedia.org/wiki/Rayleigh_distribution)

A close fit with the Rayleigh p.d.f. is beneficial as it means that approximations can be used to analyse the wind potential of the site rather than requiring detailed statistical analysis of the raw wind data. For example, it can be asserted that the average power in the wind is equal to the power found at the average wind speed multiplied by 1.91 (Masters, 2004, p. 346). This is convenient, as the power in wind is related to the cube of the wind speed, which would otherwise require analysis of the average value of wind speed cubed.

The BOM supplied weather data contains a daily field called "MeanDailyWindSpeed". The average of this value over the 10 years of data is 15.0426 km/h, or 4.1785 m/s.

Methods for determining the power output of wind turbines rely on knowing the wind speed measurements at the hub height of the turbine. The following formula (Masters, 2004, pp. 319-322) provides the approximate wind speed (v) at 31.5 metres elevation, based on the known (measured) wind speed at 10 metres:

$$v(31.5) = v(10) \times \left(\ln\left(\frac{31.5}{0.03}\right) \div \ln\left(\frac{10}{0.03}\right) \right)$$

$$v(31.5) = 4.1785 \times \left(\frac{3.021}{2.523}\right)$$

$$v(31.5) = 5.0033 \text{ m/s}$$

(where 0.03 is the roughness length for roughness class 1)

The power in wind is calculated by the following formula:

$$P_w = \frac{1}{2}\rho A v^3$$

Where P_w is the power in the wind (watts); ρ is the air density (kg/m^3); A is the cross-sectional area through which the wind flows (m^2); and v is the windspeed normal to A (m/s).

Adjusted for using Rayleigh assumptions it can be said that the average power in the wind is the power found at the average wind speed cubed multiplied by 1.91, which in this case gives:

$$P_w = 0.5 \times 1.225 \times 1 \times 5.0033^3 \times 1.91$$
$$P_w = 146.52 \text{ W/m}^2$$

(where 1.225 = standard air density kg/m^3, and the cross-sectional area is simplified to 1 m^2)

The approach used to arrive at a power output estimate for the case study turbine involves expressing the Rayleigh p.d.f in terms of average windspeed and calculating the probability of the wind at windspeeds discretized into integer steps. The probability at each windspeed is then extrapolated to a total number of expected hours per year. This is multiplied against the respective power curve data for the wind turbine at each windspeed. The probability of the windspeed at each integer step can be calculated with the following formula (Masters, 2004, p. 345):

$$f(v) = \frac{\pi v}{2\bar{v}^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{v}}\right)^2\right]$$

A spreadsheet can be setup to perform the same calculation for each windspeed integer step. The results are presented in Table 4.3.

Table 4.3

Spreadsheet solution for wind turbine power output. Average wind speed = 5.0033 m/s

Windspeed (m/s)	Power (kW)	Probability f(v)	Hrs/yr at v	Energy (kWh/yr)
0	0	0.000	0	0
1	0	0.061	533	0
2	0	0.111	970	0
3	2	0.142	1243	2,487
4	12	0.152	1331	15,971
5	24	0.143	1254	30,106
6	35	0.122	1066	37,308
7	58	0.094	827	47,970
8	95	0.067	590	56,089
9	128	0.044	390	49,874
10	161	0.027	239	38,403
11	190	0.015	136	25,795
12	213	0.008	72	15,331
13	225	0.004	36	8,007
14	234	0.002	16	3,844
15	245	0.001	7	1,736
16	254	0.000	3	726
17	261	0.000	1	281
18	265	0.000	0	101
19	271	0.000	0	34
20	267	0.000	0	10
21	263	0.000	0	3
22	259	0.000	0	1
23	253	0.000	0	0
24	248	0.000	0	0
25	245	0.000	0	0
26	0	0.000	0	0
			Total:	334,078

(Power curve source: http://www.jegaines.lt/images/product/nordexn29.pdf)

The spreadsheet solution indicates that a total of 334 MWh is produced by the case study installation.

As an aside, and to illustrate the importance of obtaining accurate wind data for use in calculations to determine power output estimates, a 20% higher average windspeed of 6 m/s was inputted into the spreadsheet. The total result was 514 MWh, which represents a 54% increase in power output..

This demonstrates the importance of selecting the right site for the turbines. At Brisbane Airport, an installation location closer to the edge of Moreton Bay may result in higher average wind speeds than those measured at the BOM weather station.

4.2.4 CASE STUDY 4 – WIND TURBINE AT BNE – RETSCREEN CALCULATIONS

In this case study the same wind turbine project parameters are used as in the previous case study, but RETScreen is again used to process the inputs and calculate the estimate of output energy produced by the system. Case studies 3 and 4 mirror the methodology applied to case studies 1 and 2.

The screen shot in *Figure 4.8* illustrates the values entered into RETScreen for the *Project Information*.

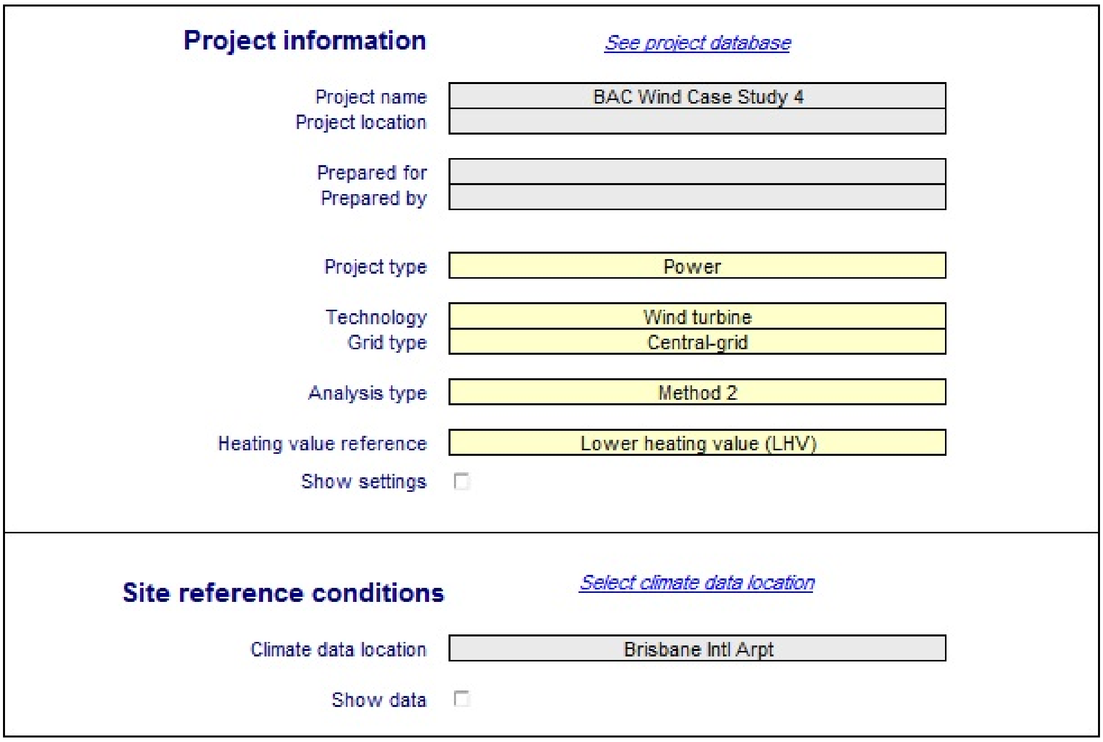
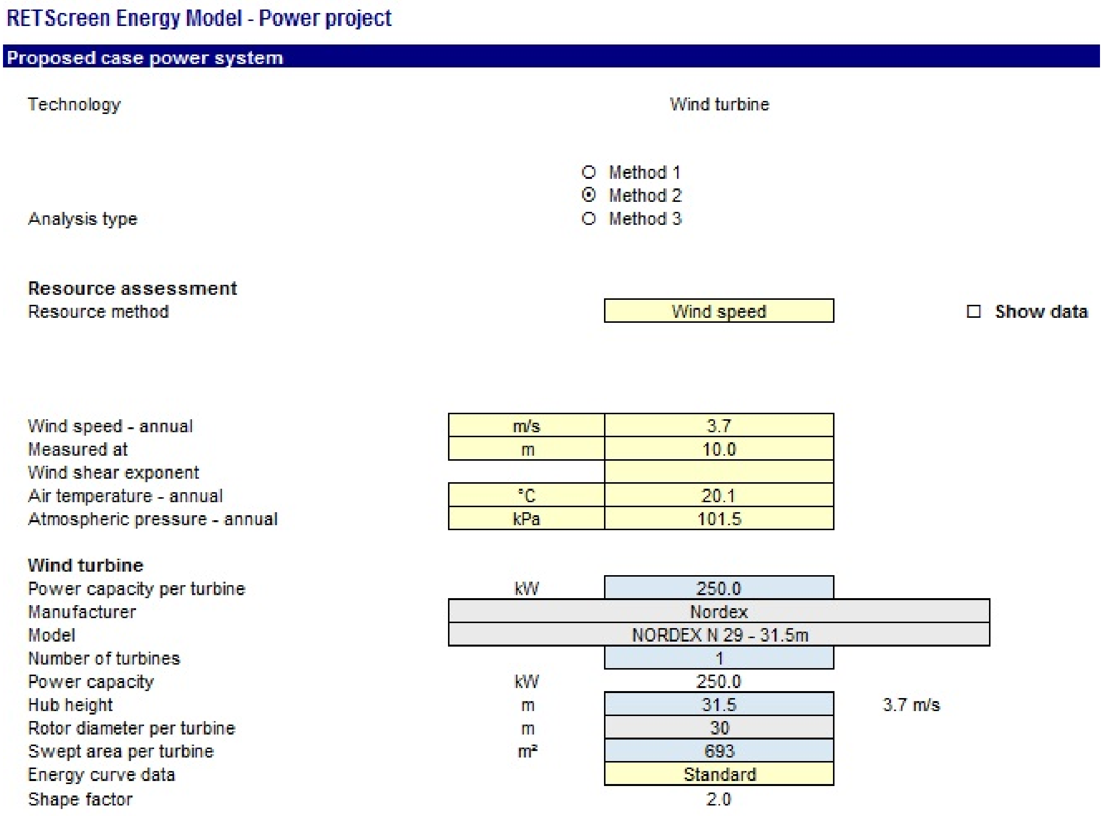


Figure 4.8. Initial Project Information data entry screen.

Once again, Brisbane International Airport was chosen as the location. The key selection on the *Project Information* screen is the *Technology* value where *Wind turbine* is selected. Case study 2 contains a description of the other settings.

After completing this screen, users move on to the next screen which is *Energy Model*. This is shown in *Figure 4.9* and *Figure 4.10*.



RETScreen Energy Model - Power project

Proposed case power system

Technology		Wind turbine	
Analysis type		○ Method 1 ⦿ Method 2 ○ Method 3	
Resource assessment			
Resource method		Wind speed	☐ Show data
Wind speed - annual	m/s	3.7	
Measured at	m	10.0	
Wind shear exponent			
Air temperature - annual	°C	20.1	
Atmospheric pressure - annual	kPa	101.5	
Wind turbine			
Power capacity per turbine	kW	250.0	
Manufacturer		Nordex	
Model		NORDEX N 29 - 31.5m	
Number of turbines		1	
Power capacity	kW	250.0	
Hub height	m	31.5	3.7 m/s
Rotor diameter per turbine	m	30	
Swept area per turbine	m²	693	
Energy curve data		Standard	
Shape factor		2.0	

Figure 4.9. Top section of the Energy Model form

☑ Show data

Wind speed m/s	Power curve data kW	Energy curve data MWh
0	0.0	
1	0.0	
2	0.0	
3	2.0	73.2
4	12.0	180.7
5	24.0	334.9
6	35.0	515.8
7	58.0	702.4
8	95.0	880.8
9	128.0	1,043.3
10	161.0	1,186.0
11	190.0	1,307.2
12	213.0	1,405.8
13	225.0	1,481.9
14	234.0	1,535.9
15	245.0	1,569.7
16	254.0	
17	261.0	
18	265.0	
19	271.0	
20	267.0	
21	263.0	
22	259.0	
23	253.0	
24	248.0	
25 - 30	245.0	

Array losses	%	
Airfoil losses	%	
Miscellaneous losses	%	
Availability	%	100.0%
Summary		
Capacity factor	%	6.7%
Electricity exported to grid	MWh	146

Figure 4.10. Bottom section of the Energy Model form

At this point, RETScreen has all the data it requires and calculates that the hypothetical scenario would produce 146 MWh per annum. This figure can be seen in the *Electricity exported to grid* section of *Figure 4.10*.

This is obviously quite a variation from the figure calculated in case study 3 of 334 MWh. Analysis and discussion of this difference will be conducted in the next chapter.

4.2.5 CASE STUDY 5 – DECISION OPTIMISATION AND SENSITIVITY ANALYSIS

Decision Optimisation

This case study assumes a hypothetical scenario where a decision is to be made to select one of the two RET options from the earlier case studies:

- Alternative 1 – Rooftop solar PV DFO centre
- Alternative 2 – 10 x Nordex N29 wind turbines

The performance modelling data is taken from the RETScreen case studies. This case study provides an example of using other items from the decision support resource kit formed in Chapter 3 to enhance decision making. In particular, sustainability criteria are included in the decision making criteria seeking to be optimised, and Decision Deck-diviz is used to conduct the MCDA processing. The intention is to provide an overview of how the various components fit together, rather than a detailed analysis of MCDA techniques, therefore a reasonably simple scenario will be examined, using a weighted sum MCDA algorithm.

The first step is to define the decision criteria. Examples of airport sustainability criteria were reviewed in Chapter 2. Each airport would need to consider the criteria that it regards as important, and consider criteria from the economic and social dimensions, as well as environmental. For example, the following could be used:

- Increase in MWh per annum from RET supply (c1)
- Internal rate of return (IRR) (c2)
- Projected complexity rating of planning and other approvals process (c3)
- Visibility rating of project as a statement of commitment to sustainability (c4)

Then, assume the following performance table for the two alternatives against these four criteria:

Table 4.4
Decision analysis performance table

Criteria	Alternative 1 – Solar PV	Alternative 2 - Wind	Goal
c1	2438	146 x 10 = 1460	MAX
c2	12%	15%	MAX
c3	2/5	4/5	MIN
c4	3/5	5/5	MAX

*Hypothetical values used for c2-c4

The next step is to formulate utility functions that can be used to measure the performance of the alternatives against the criteria on a normalised scale. 0-1 is used as the scale, with 0 indicating the alternative has no utility for the criteria and 1 meaning it completely satisfies the criteria. Linear functions are used for simplicity.

Table 4.5

Criteria utility functions

Criteria	Utility Function
c1	$f(x) = \begin{cases} 0, & x < 1000 \\ 1, & x \geq 2500 \\ \frac{x-1000}{1500}, & 1000 \leq x < 2500 \end{cases}$
c2	$f(x) = \begin{cases} 0, & x < 0.08 \\ 1, & x \geq 0.20 \\ \frac{x-0.08}{0.12}, & 0.08 \leq x < 0.20 \end{cases}$
c3	$f(x) = \frac{5-x}{5}$
c4	$f(x) = \frac{x}{5}$

The performance table can now be transformed into utility values, and a weighting is assigned to indicate the relative importance of each criteria.

Table 4.6

Performance table results

Criteria	Alternative 1 – Solar PV	Alternative 2 - Wind	Weighting
c1	0.96	0.3	0.3
c2	0.33	0.58	0.2
c3	0.6	0.2	0.2
c4	0.6	1.0	0.3

The next step is to populate the inputs for Decision Deck-diviz. This is done by creating four xml files. These files contain the alternatives, the criteria, the criteria weights, and the performance table. A workflow is then configured on the application canvas which involves connecting the inputs with algorithms. The appearance of the configured workflow in diviz for the case study is depicted in *Figure 4.11*

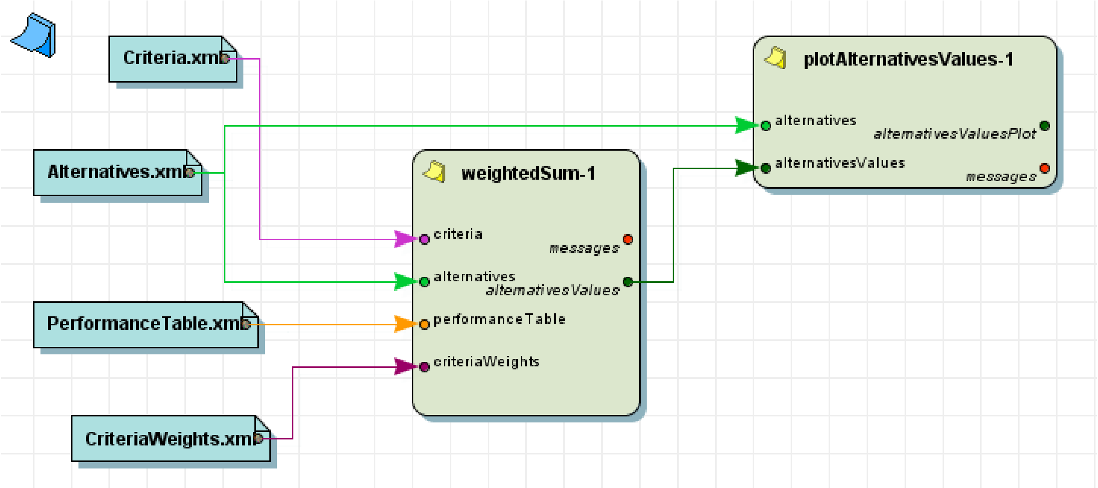


Figure 4.11. Configuration of Decision Deck-diviz application

From this point, the decision analysis can be computed, and a graphical output can be produced, which is shown in *Figure 4.12*

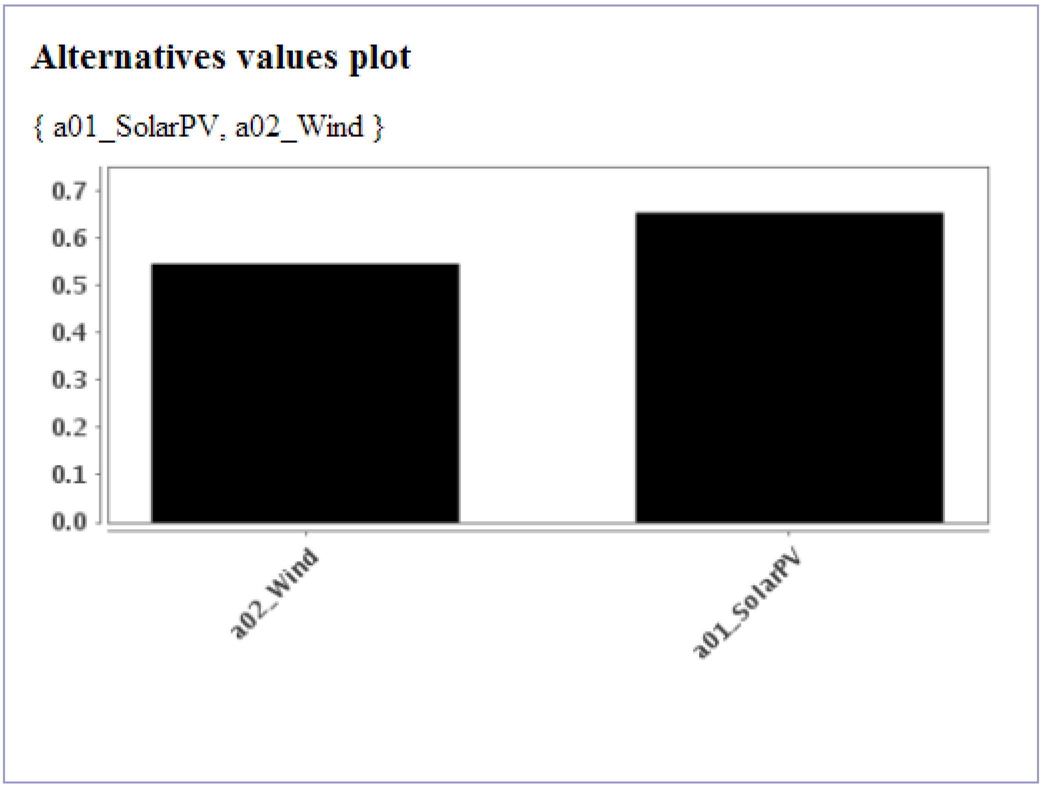


Figure 4.12. Graphical display of decision analysis result

Based on the hypothetical attributes of the case study, the Solar PV alternative obtained the higher performance rating from the weighted sum algorithm. Decision Deck-diviz is a convenient and accessible software tool to assist in the applying of MCDA techniques to sustainable energy decision making.

Sensitivity Analysis

In this section, another hypothetical rooftop solar PV project serves as a baseline scenario and the decision analysis process is used to conduct a sensitivity analysis. This serves as a guide in how to implement such analysis and incorporate it into the decision process, and also to build an understanding of likely factors that dominate decision criteria in similar scenarios. Real-world data is used where possible, supplemented by accurate estimates. Table 4.7 below lists the parameters of the case study that form the baseline case.

Table 4.7

Parameters of case study

Parameter	Value	Source
DC System size	99.9kWp	

Location	Brisbane Airport	
Installation Type	Fixed roof mount, tilt 0°	
Annual AC Production	139 MWh	http://pvwatts.nrel.gov
Installation Cost	AUD $204,416	[4]
Maintenance Cost	1.5% per annum cap ex cost	[4]
Project Life-time	20 years	
Electricity supply cost (excl. fixed connection charge)	AUD $0.236/kWh	[5]
Electricity cost inflation %	2%	[6]
Maintenance cost inflation %	2.8%	[7]
Discount Rate	10%	
GHG Reduction Factor	0.81 kg CO_2-e/kWh	[8]

A discount rate of 10% was selected based on a major airport's cost of capital being in the range of a few extra percentage points on top of a risk-free interest rate of 2-3%, and an additional premium for the long-term nature of the project.

The decision criteria selected for this case study are:

- Net Present Value (NPV) (c1)
- Internal Rate of Return (IRR) (c2)
- Reduction in Greenhouse Gas Emissions (c3)

[4] Estimate courtesy of Infinity Power Pty Ltd at AUD $2.046/Watt
[5] http://www.qca.org.au/Electricity/Electricity-Prices-2014-15/Electricity-prices-2014-15/Electricty-Prices-Business-Tariffs Tariff 20
[6] AEMO – National Electricity Forecasting Project - QLD
[7] RBA calculator – average inflation rate 2005-2014
[8] Australian National Greenhouse Accounts Factors December 2014, http://www.environment.gov.au/system/files/resources/b24f8db4-e55a-4deb-a0b3-32cf763a5dab/files/national-greenhouse-accounts-factors-dec-2014.pdf section 2.3.1

A spreadsheet solution was created to determine the NPV and IRR. The GHG emissions reduction, in tonnes, for the 139MWh of grid supply displaced by the solar production is estimated as follows:

$$= 139{,}000 \times (\frac{0.81}{1{,}000})$$

$$= 112.59\ tonnes\ \mathrm{CO_2 - e}$$

Table 4.8 lists the performance table for the baseline case

Table 4.8

Decision analysis performance table

Criteria	Baseline Case	Goal
c1	AUD $118,716.93	MAX
c2	17%	MAX
c3	112.59 t CO_2-e	MAX

The sensitivity analysis is performed on the following variations to the baseline case:

Table 4.9

Variation scenarios

Variation	Adjustment
v1	Installation Cost +30%
v2	Installation Cost -30%
v3	Maintenance Cost +30%
v4	Maintenance Cost -30%
v5	Project Lifetime 30 years
v6	Electricity Supply Cost +30%
v7	Electricity Supply Cost -30%
v8	Electricity cost inflation % +30%

v9	Electricity cost inflation % -30%
v10	Maintenance cost inflation % +30%
v11	Maintenance cost inflation % -30%
v12	Discount Rate % +30%
v13	Discount Rate % -30%
v14	Annual AC Production +30%
v15	Annual AC Production -30%

The table below lists performance results for the three criteria across all 15 variation scenarios.

Table 4.10

Variation scenarios performance table

Variation	NPV (c1)	IRR (c2)	GHG Reduction (c3)
v1	$46,730.06	11%	112.59 t CO_2-e
v2	$190,703.79	27%	112.59 t CO_2-e
v3	$108,054.86	16%	112.59 t CO_2-e
v4	$129,378.99	17%	112.59 t CO_2-e
v5	$162,121.35	17%	112.59 t CO_2-e
v6	$226,318.87	24%	112.59 t CO_2-e
v7	$11,114.99	10%	112.59 t CO_2-e
v8	$134,707.89	17%	112.59 t CO_2-e
v9	$103,707.13	16%	112.59 t CO_2-e
v10	$116,408.15	17%	112.59 t CO_2-e
v11	$120,827.72	17%	112.59 t CO_2-e
v12	$64,034.88	16%	112.59 t CO_2-e

v13	\$196,194.82	17%	112.59 t CO_2-e
v14	\$226,318.87	24%	146.37 t CO_2-e
v15	\$11,114.99	10%	78.81 t CO_2-e

Based on this performance table, utility functions have been created that return normalised results between 0 and 1. The functions are listed below in Table 4.11.

Table 4.11

Criteria utility functions

Criteria	Utility Function
c1	$f(x) = \begin{cases} 0, & x < 10000 \\ 1, & x \geq 230000 \\ \dfrac{x - 10000}{220000}, & 10000 \leq x < 230000 \end{cases}$
c2	$f(x) = \begin{cases} 0, & x < 0.1 \\ 1, & x \geq 0.27 \\ \dfrac{x - 0.1}{0.17}, & 0.1 \leq x < 0.27 \end{cases}$
c3	$f(x) = \begin{cases} 0, & x < 75 \\ 1, & x \geq 150 \\ \dfrac{x - 75}{75}, & 75 \leq x < 150 \end{cases}$

Table 4.12 lists the performance table of the results from the utility functions applied to the raw performance results.

Table 4.12

Variation scenarios normalised performance table

Variation	c1	c2	c3
v1	0.167	0.059	0.501
v2	0.821	1.000	0.501
v3	0.446	0.353	0.501
v4	0.543	0.412	0.501

v5	0.691	0.412	0.501
v6	0.983	0.824	0.501
v7	0.005	0.000	0.501
v8	0.567	0.412	0.501
v9	0.426	0.353	0.501
v10	0.484	0.412	0.501
v11	0.504	0.412	0.501
v12	0.246	0.353	0.501
v13	0.846	0.412	0.501
v14	0.983	0.824	0.952
v15	0.005	0.000	0.051
Weighting	0.33	0.33	0.34

The weightings in this case have been selected to be uniformly distributed, and will not be modified for sensitivity analysis. Adjusting the weightings will affect the outcome, but the values used in practice are subjective and need to be based on the context of a specific project. Once weightings are established (e.g. via a stakeholder poll) then sensitivity analysis can be performed on them.

These inputs were run through Decision Deck-diviz and the chart in *Figure 4.13* displays the results.

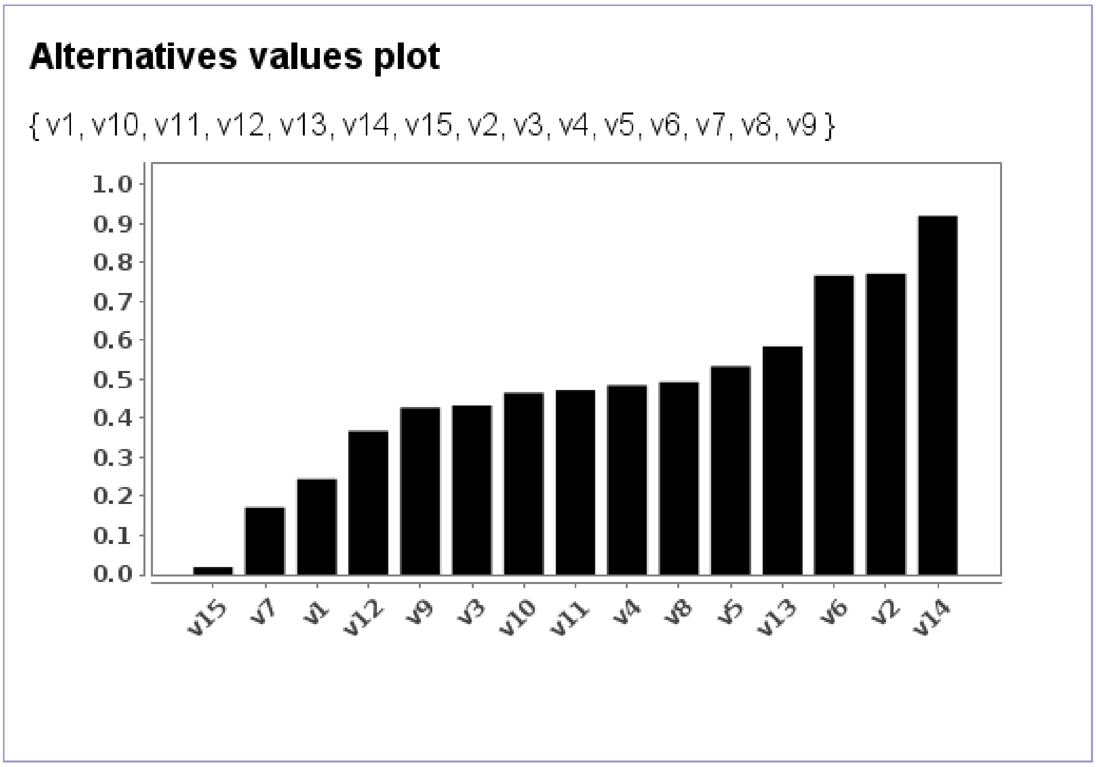


Figure 4.13. Results of sensitivity analysis

The results reveal that the 3 variations that most significantly had a positive effect on the outcome were (in order):

- v14 Annual AC Production +30%
- v2 Installation Cost -30%
- v6 Electricity Supply Cost +30%

And the top 3 variations that had a negative impact were:

- v15 Annual AC Production -30%
- v7 Electricity Supply Cost -30%
- v1 Installation Cost +30%

The remainder of the variations only had marginal impact on the outcome. Altering Annual AC Production was the most significant variation, in both directions, demonstrating the two-fold impact of the output from the solar PV system in both increasing (or decreasing) electricity consumption, and increasing (or decreasing) GHG emissions, therefore impacting both financial and environmental criteria. The same financial criterion impact is achieved when electricity price is reduced by 30%, as it is when increasing annual AC production by 30%, but this does not impact GHG emission reduction.

Chapter 5: Analysis

5.1 CASE STUDY 1

Case study 1 was based on a methodology of manually retrieving reference data (weather data, product data) and then applying calculations.

It has shown that typical large buildings on airport sites can host substantial solar PV panel installations. It was noted that a cost-benefit analysis is necessary to determine for each project the most appropriate installation type. An extra 10% or more of input energy can be harnessed by panels that are tilted to an optimal angle versus panels that are fixed to a horizontal roof. Even more input energy can be harnessed by tracking the sun.

The case study installation was demonstrated to be capable of producing approximately the same amount of electricity as is consumed by the chosen building. This does not mean that the building is independent of the electricity grid, as the building will require power at times when the panels are not generating, or only generating at partial capacity (e.g., Night time, and cloudy days), and there will be times when the panels are producing surplus to the buildings needs.

The net electricity cost position of the project will depend on additional factors, for example the price available to the building for any surplus sold back to the grid. There are a number of schemes that are used for determining the price for surplus electricity:

a) Bi-directional meter. This is an older scheme whereby the meter spins backwards when net electricity is being delivered to the grid.

b) Net metering. Two meters are installed, the import meter for electricity supplied from the grid, and the export meter for electricity supplied to the grid. The system is configured such that only electricity excess to the building's consumption is sent to the grid, and therefore registered in the export meter for purchase by the electricity supplier.

c) Gross metering. Two meters are installed, like net metering, but the system is configured so that all electricity produced is dispatched to the grid and measured by the export meter for purchase by the electricity supplier, and all electricity for the buildings consumption is supplied from the grid.

d) Feed-in tariff. These schemes put in place a premium price paid for electricity sent to the grid. For example, if the retail cost of electricity is 15 cents/kWh then the feed-in tariff price might be 30 or 40 cents/kWh. These schemes are common around the world. In Germany, an early adopter of a broad and generous scheme, it was primarily responsible for a large uptake of solar PV installations. Germany has a little more than half of the available average insolation that Australia does, but during the early to mid-2000's the uptake of solar PV was much higher. This is shown in *Figure 5.1*.

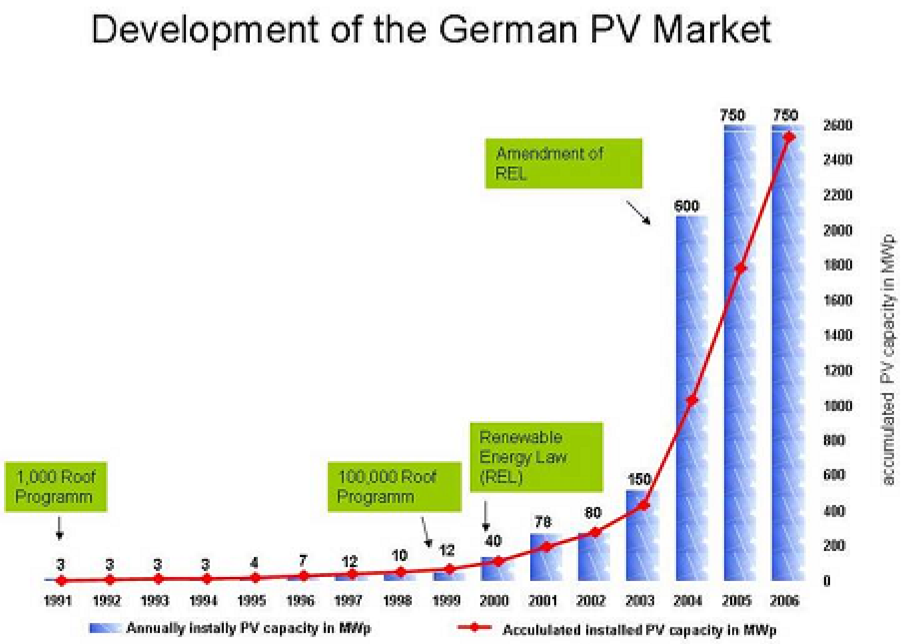


Figure 5.1. Solar PV uptake in Germany.

(source: European Photovoltaic Industry Association - http://www.epia.org/datafigures/europe.html)

The chart illustrates the dramatic increase in solar PV uptake after the feed-in tariff was introduced initially in the year 2000.

More recently, schemes have been introduced in Australia. This has also prompted a large increase in the uptake of solar PV, in particular, by small-scale systems such as domestic roof-top installations. This is shown in *Figure 5.2*.

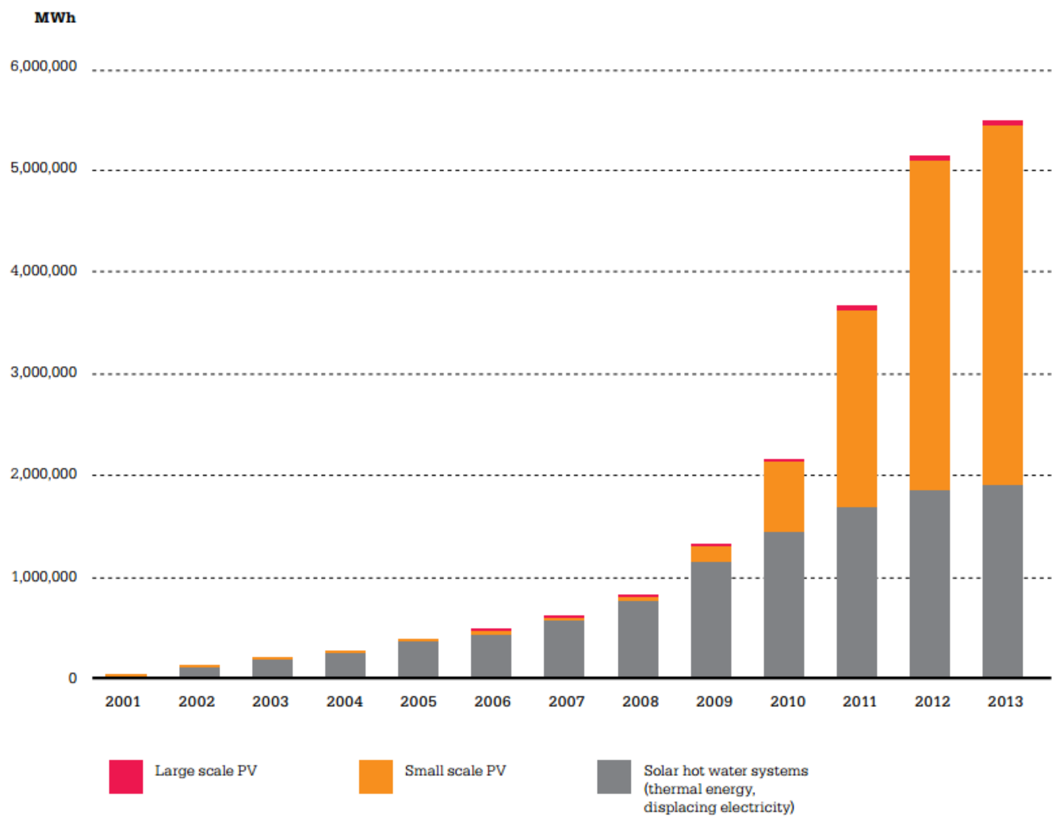


Figure 5.2. Solar uptake in Australia

(source: Climate Commission Report (Flannery & Sahajwalla, 2013))

Many authorities choose to implement a net feed-in tariff scheme, one motivation being that it places an onus on system owners to minimise their electricity consumption if they wish to maximise their exports. This provides an incentive to be more efficient with energy consumption.

This case study was confined to a roof-top installation, but the benefits are equally applicable to other types of installation at airports, including open field systems, and car-park shading structures that incorporate solar PV panels.

5.2 CASE STUDY 2

Case study 2 consisted of running a simulation in RETScreen of a solar PV project with the same parameters as case study 1. The final result that RETScreen calculated, contained in the bottom line *Electricity exported to grid*, is an estimation of 2,438.5 MWh per year of electricity produced by the hypothetical system.

RETScreen was seen to be very easy to use as a piece of software. It is embedded within the Microsoft Excel spreadsheet package, which is familiar to computer users across the world. And its extensive weather and product database make selecting parameters to match real-world conditions an easy task.

On a usability scale it ranks very highly. In addition, it has an online knowledge base for support purposes. And training courses are available at numerous times and locations worldwide.

There are 330,207 users of RETScreen in 222 countries[9]. User numbers of this scale imply that the product is thoroughly used and that a cohort of expert users and a knowledge base exists around the software product itself in order to provide support to users.

5.3 COMPARISON OF CASE STUDY 1 AND 2

The results from case study 1 and 2 are presented in Table 5.1:

Table 5.1

Final results of case study 1 and case study 2

Case Study	Result
Case Study 1	2270.3 MWh
Case Study 2	2438.5 MWh
Difference	7.5%

This modest difference of 7.5% is a reasonably close result, especially when considering that both methodologies have to make assumptions about the value of losses from items such as dirt, cabling and temperature de-rating.

The level of imprecision inherent in making assumptions means that a 7.5% difference is quite acceptable and is no barrier to taking these results as reinforcing the acceptability of this software as a component of the proposed resource kit.

It should be noted that RETScreen has many other features in addition to those which were displayed in case study 2. In particular, it contains an emissions analysis module, a financial analysis module and a sensitivity and risk module.

[9] http://www.retscreen.net/ang/home.php, accessed on 21 March 2012.

The emissions analysis module allows a business as usual baseline to be evaluated against the sustainable energy alternative. Three types of analysis are supported. The first, standard analysis, is the most simple and uses fuel and emission factors as recommended by the International Panel on Climate Change (IPCC) and industry standard values. The second type, custom analysis, allows the user to update any of the various factors as required, and the third type, user-defined analysis, allows the direct entry of final values that were calculated by the user outside of the package.

The financial analysis module allows a cumulative cashflow analysis to be conducted. It also provides a number of key financial indicators such as net present value (NPV), internal rate of return (IRR) and simple payback.

The sensitivity and risk module gives the user an analysis of the sensitivity of the project to changes in various variables. In assessing the feasibility of a project there is an inherent degree of uncertainty over input parameters. The significance of possible errors or mistakes in input parameters can be determined by conducting the sensitivity analysis. The following types of sensitivity analysis are catered for:

- Monte Carlo simulation
- Level of risk
- Influence of parameters

5.4 CASE STUDY 3

Just like case study 1, this case study was based on a methodology of obtaining reference data (weather data, product data, and so on) and then manually applying calculations, this time for a hypothetical wind project.

It was noted that with wind power projects, the amount of energy available to be harnessed increases with the cube of the wind speed. This sensitivity to wind speed highlights the need for rigorous analysis of any potential real-world wind project to assure the forecasts in output are as close to reality as possible.

The calculations in case study 3 resulted in an estimated annual output of 334 MWh for the hypothetical wind turbine project.

5.5 CASE STUDY 4

In this case study, RETScreen estimated an annual electrical output of 146 MWh. As with case study 2, it was seen that RETScreen was very easy to use for the purposes of assessing the feasibility of a wind turbine power project. It was a simple matter of selecting the type of wind turbine from the product database and the location from the meteorological database.

5.6 COMPARISON OF CASE STUDY 3 AND 4

The results from both case study 3 and 4 are presented in Table 5.2

Table 5.2

Final results of case study 3 and case study 4

Case Study	Result
Case Study 3	334 MWh
Case Study 4	146 MWh
Difference	129%

The difference between the results of the two case studies is significant. More detailed investigation is required to understand the reasons behind the difference.

Reviewing the two case studies, it is apparent that there is a difference in wind speed assumptions. It is only logical, given the previously mentioned sensitivity of wind turbine output to wind speed, that this is a significant reason for the variation in results.

In case study 4, the RETScreen model was based on a 3.7m/s wind speed, while the manual calculations in case study 3 rely on a wind speed of 4.1 m/s observed at the 10m elevation anonometer. In addition to this, in the manual method of case study 3, the wind speed was increased further by extrapolating what the speed would be at the hub height of the turbine (31.5 m).

Wind speeds increase as distance from the ground increases (and therefore friction from the ground decreases). The wind speed meeting the blades at the top of the revolution of a turbine will be higher than that meeting the blades at the bottom of the turbine. Taking the speed at the hub height is effectively taking an average between those two extremes.

From *Figure 4.9* it can be seen that, while RETScreen does seem to be utilising the wind speed as at the hub height (as opposed to the anonometer height), it is not calculating an uplift factor for estimating the wind speed at the hub height. It is using the same speed as measured at 10 m - that is, 3.7 m/s. The two case studies are therefore using quite different wind speed assumptions; 5.0033 m/s for case study 3 and 3.7 m/s for case study 4.

In order to determine whether this is the primary explanation for the difference between case studies, the spreadsheet model used in case study 3 was updated to use a wind speed of 3.7 m/s instead of 5.0033 m/s. The result was 141 MWh hours. This is very close to the RETScreen result and therefore it is likely that this was the significant reason for the difference.

5.7 CASE STUDY 5

In case study 5, Decision Deck-diviz was evaluated by performing an example decision analysis to compare two alternative sustainable energy proposals that had been through RETScreen pre-feasibility screening.

The scenario was a simplistic one, but it served the purpose of demonstrating that the software tool was easy to use and supports the various features required to conduct decision analysis. In fact, it has a large number of MCDA algorithms available including many variants of weighted sum and outranking methods, and therefore is capable of handling much more complicated scenarios and assessments than presented in this case study. There is also a large range of help and support resources available to assist users.

A second decision support scenario was run through Decision Deck-diviz to perform a sensitivity analysis on variations to the parameters of a solar PV rooftop project. It was seen that the most significant factor influencing the outcome was the electricity production from the solar system. This was the most significant positive impact when the production was increased by 30%, and also the most significant negative impact when production was decreased by 30%.

This highlights the importance of accurate system production estimates in the planning stages of a project. Inaccurate estimates can result in significant discrepancies between the expected profile of a system and the actual operating profile. If software tools are being used to generate production estimates then assurances of accuracy are very important.

5.8 DISCUSSION

The case studies have provided example usage and insight into key components of the resource kit. There is no evidence to suggest that either software tool is not a good fit for its purpose.

In light of the assessment of these two software tools, the decision making process that an Airport Metropolis decision maker would follow if they were to use the decision support framework and resource kit is summarised below:

- Stakeholder engagement. This includes, for example, airport staff, airport tenants, local communities, government agencies, elected officials. The establishment of a sustainable energy working group might help achieve good engagement. This will provide an insight into the priorities and views of the various stakeholders.
- Nomination of sustainability champion(s). This person, or persons, will serve as a central point of focus and be the driving force behind achieving outcomes.
- Knowledge acquisition. Using the Chicago Department of Aviation Sustainable Airport Manual as a starting point, embark on a program of learning to discover what options available, and what the current state of world's best practice is in this domain.
- Pre-feasibility assessment. Using this knowledge gained, identify a number of candidate projects. Use RETScreen to conduct a pre-feasibility assessment of each of those projects.
- Sustainability indicators. Use GRI v4 for defining and establishing a set of suitable indicators that will provide the basis for measuring projects and progress.

- Decision analysis. In order to get an assessment of the relative merits of alternative options, use Decision Deck-diviz software. Following an MCDA approach is intended to guide the airport to making the optimal decision.
- Decision implementation. Approve the project and follow it through to implementation.
- Reporting and compliance. Report sustainability measures by adopting the GRI v4 framework, and ensure adherence to best quality practices and processes by achieving certification against ISO 50001.

With regard to a possible future DSS, it is important to assess how these software components could be integrated into such a system.

RETScreen, being built within Microsoft Excel, has limited options for direct integration. At best, a tightly coupled interface could be built that used the VBA automation capabilities of Excel in order to provide input values programmatically (i.e. from the DSS) as an alternative to entering manually via the Excel user interface. Output values would be returned programmatically as well. This would provide the benefit of being able to build a user interface in the DSS that had sliders for various input parameters and allowed the dynamic assessment of various options.

For example, the DSS could feature a GIS user interface. This would give users the ability to interact spatially with their airport, for example to dynamically locate and size roof-top solar arrays, and review the calculated system generation potential. Green roof options could similarly be experimented with.

From a software engineering perspective, the drawback of a tightly coupled interface is that it is brittle, and prone to support and maintainability issues. The DSS, or middleware code, must be hard-coded with the addresses or names of specific cells in the Excel spreadsheet. These might change when the RETScreen software is upgraded.

A better solution is to use an API, such as a web API built on the SOAP or REST protocol. This allows HTTP requests (a ubiquitous platform) to send and receive data between the client (the DSS) and the service (RETScreen). API's are more easily made backwards compatible between releases, thereby minimising the possibility of breaking existing code or clients. Future work by the RETScreen team to increase the utility of their software by adding such a flexible programmatic interface into the back-end sustainable energy calculation "engines" inside RETScreen would be highly beneficial.

Decision Deck-diviz is built on a foundation of open standards including XML, meaning that it is easier to integrate it into other software systems. The Decision Deck project has a feature called XMCDA web services which support SOAP web service requests to an online service which provides the same functionality as that available in the desktop application that was demonstrated in the case study. This provides a great opportunity for decision analysis functionality to be integrated into a DSS.

Chapter 6: Conclusions

This chapter completes this thesis by focusing on conclusions, limitations, implications and recommendations flowing from the research. In the introduction, a need was identified for research that assists Airport Metropolis stakeholders to streamline and optimise their decision making process around sustainable energy use. The research objective was to meet this need by investigating and creating a unified decision support framework and resource kit that could guide and assist Airport Metropolis decision makers.

6.1 SUMMARY

Firstly, a brief summary of the earlier chapters: Chapter 2 was a literature review into topics connected with sustainability of energy use at Airport Metropolises and optimising decision making.

Chapter 3 presented and discussed a decision making framework and resource kit targeted at optimising decision making in this area, and described a number of case studies designed to test and demonstrate key resource kit items.

Chapter 4 was the execution of the five case studies. Chapter 5 contained analysis and discussion based on the results of the case studies.

6.2 CONCLUSIONS

The evidence provided by the case studies was that the software tools involved, namely RETScreen and Decision Deck-diviz, can be described as mature and easy to use. RETScreen has been in production since 1998, and is currently up to its fourth major release, which indicates it is a mature product. It includes an extensive database of weather and product data, and supports a large number of sustainable energy project types, which indicates its sophistication.

It was seen that the results obtained by using RETScreen matched closely with the results obtained from using manual calculations, but with one important caveat. With the wind project, the initial results were not closely matched, and it was only after investigating the assumptions being used in the RETScreen model that the reason for the discrepancy was discovered – a different assumption in average wind speed. After accounting for this, the results were much more closely matched.

Understanding what was going on “under the covers” of RETScreen - knowing that it was not factoring an increase in windspeed from the speed measured at 10 metres altitude up to an expected speed at the hub height of the turbine - is not a trivial exercise, and certainly not one that could be expected of an Airport Metropolis decision maker who is likely to be skilled at dealing with airport issues, but not have expertise in renewable energy calculations.

This leads to the conclusion that while the software tools are indeed powerful, there is not yet an expectation that they can be used solely in a “self-service” mode. This is not to say that they can’t be used initially in self-service mode, but at some point during the planning and decision making cycle, additional human expertise is required for quality assurance purposes.

6.3 IMPLICATIONS

This section contains commentary on the broader implications. Numerous real-world examples have highlighted great lengths that many airports around the world have gone to in pursuit of the goal of incorporating sustainable practices into their energy consumption.

It is a practical and commercial reality and those airports that ignore these opportunities may well be left behind. The extent of the potential divergence between airports that embrace sustainable energy practices and those that don’t can be analysed further by referring to the three broad areas of sustainability - economic, environmental, and social.

On the economic front, airports are businesses that are in competition with other businesses to make a profit. In a large city that has a number of airports servicing it, airlines and other tenants who value sustainability can shift business away from an airport that is regarded as not embracing it.

In addition, as carbon pricing schemes are phased in and ramped up they will adversely affect fossil fuel dependent airports. Therefore, it is certainly possible for airports not embracing sustainable energy alternatives to suffer economically.

When it comes to environmental concerns, airports that increase sustainability are obviously contributing to the protection of the world's environment, and safeguarding it for future generations so that they enjoy the same (or better) living standards as current and previous generations.

And thirdly, the social dimension. Airports are not isolated islands. They are interwoven with their surrounding communities and cities. The social fabric is strengthened by having airports that are good corporate citizens and are committed, not only to their own success, but the success of the community they operate in. In addition, airport staff may value working for an organisation that operates in this manner.

Airports that do not meet this standard will see the deterioration of their “licence to operate”, something which is granted to them by their local communities. Fossil fuels are a finite resource and they are being depleted at an accelerating rate. Alternatives exist that can supply Airport Metropolises with more sustainable forms of energy. And the costs of these alternatives are decreasing as they are more widely adopted and economies of scale drive prices down.

The material presented in this thesis provides evidence that some airports around the world have already begin to embrace sustainable energy options and have been able to do so in a commercially sound and effective manner.

With regard to the implications for a possible future DSS, the conclusion above about the ability of the software to be used in “self-service” mode raises the question as to what extent a DSS framework can provide the required oversight. It is possible that elements of such human expertise could be incorporated into a DSS. This could be achieved, for example, by constraining the parameters of the available back-end energy models to values that are practical in the Airport Metropolis context. This combines the best of both worlds. It puts the decision-makers in control of the software tools, but in such a way that they are guided by expert and domain specific knowledge.

The proliferation of devices such as smart meters means that organisations are already collecting vast amounts of data related to the day-to-day operations of their energy systems. Many airports already have implemented building/energy management systems. This data should also be within the scope of such a DSS, because it provides more detail about the "as is" situation and leads to richer capabilities in contrasting it with hypothetical "to be" scenarios being modelled.

6.4 LIMITATIONS

A recognised limitation of this study is that there was no scope to provide a more detailed investigation of RETScreen's features. Only two of the project types were used - solar PV and wind turbine projects. There are in fact over forty project types available.

6.5 RECOMMENDATIONS

A number of recommendations are made for Airport Metropolis decision makers.

It would be beneficial for them to open channels of communication with airports featured in this research that are world leaders in sustainable energy. They should seek to conduct site visits to be able to see first-hand how the projects have been implemented and hear about the commercial arrangements put in place to accommodate them and hear about the suppliers and contractors that were used on the projects.

They should establish their own sustainable energy working groups, and sustainability champions, to be a focal point for all activities at the airport related to this area. For example, this group would be tasked with establishing a baseline of energy usage. It could develop processes for the ongoing measurement of energy use and a method for dispersing that information to the general public on a regular basis, for example via the airport’s web site. Its existence will help to close the feedback loop so that assessments can be made of the effectiveness of implemented sustainable energy projects.

They should enrol a number of staff in RETScreen training so that they acquire a broad skill base in assessing the pre-feasibility of sustainable energy projects. As an outcome of this training, these staff will develop knowledge of sustainable energy topics and will become more adept in general at communicating the concepts with other stakeholders such as consultants, regulators, airport boards, and so on.

A number of recommendations are also made for future research. The first recommendation is in the area of assessing actual performance versus pre-build estimates of performance.

This topic would see a catalogue of comparisons created for a variety of sustainable energy projects at large airports. This would require the cooperation from the airports involved in order to obtain performance data. But it would be very valuable for future project teams to gain insights into real-world discrepancies that have existed between project estimates (such as seen with the case studies in this thesis) and actual performance. There may be some valuable "lessons learned" that other airports could benefit from.

The second recommendation is that further research and development is conducted into building a sustainable energy DSS that can provide the bridge between Airport Metropolis decision makers and software such as that investigated here.

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Appendices

APPENDIX A: SOURCE CODE LISTING

The source code is written in Javascript and is embedded into a HTML web document.

```
<script type="text/javascript">

//<![CDATA[

  // Helper Function
  Array.prototype.indexOfMaxValue = function () {

    var maxVal = -500;
    var indexOfMax;
    for (var i = 0; i < this.length; i++) {
      if (this[i] > maxVal) {
        indexOfMax = i;
        maxVal = this[i];
      }
    }
    return indexOfMax;
  };

  var map;

  function load() {
    if (GBrowserIsCompatible()) {

      var numPoints = 0;
      var lats = new Array(4);
      var longs = new Array(4);

      map = new GMap2(document.getElementById("map"),
              { size: new GSize(800, 600) });
      map.removeMapType(G_HYBRID_MAP);
      map.setCenter(new GLatLng(-27.3838, 153.119878), 17);
      map.addControl(new GLargeMapControl());

      var mapControl = new GMapTypeControl();
      map.addControl(mapControl);

      map.setMapType(G_SATELLITE_MAP);

      GEvent.addListener(map, 'click', function (overlay, latlng) {
        lats[numPoints] = latlng.lat();
        longs[numPoints] = latlng.lng();
        var point = new GLatLng(lats[numPoints], longs[numPoints]);
        map.addOverlay(new GMarker(point));
        numPoints = numPoints + 1;
        if (numPoints == 4) {
          var polygon = new GPolygon([
                          new GLatLng(lats[0], longs[0]),
                          new GLatLng(lats[1], longs[1]),
                          new GLatLng(lats[2], longs[2]),
                          new GLatLng(lats[3], longs[3]),
                          new GLatLng(lats[0], longs[0])
```

```
                    ], "#f33f00", 4, 1, "#ff0000", 0.2);
          // Clear the point markers before adding the new polygon
          map.clearOverlays()
          map.addOverlay(polygon);
          // Add an info window with the Area of the polygon
          var latsIndexForPopup;
          latsIndexForPopup = lats.indexOfMaxValue();
          map.openInfoWindowHtml(new GLatLng(lats[latsIndexForPopup],
longs[latsIndexForPopup]),
                            "<div style='font-family: Arial'>Area: <strong>" +
polygon.getArea().toFixed(2) + "</strong> m2</div>");
          numPoints = 0;
        }
      });
    }
  }

  function clearOverlays() {
    map.clearOverlays();
    numPoints = 0;
  }

//]]>

</script>
```

APPENDIX B: CASE STUDY 5 DIVIZ XML DOCUMENTS

Alternatives.xml

```
<xmcda:XMCDA xmlns:xmcda="http://www.decision-deck.org/2009/XMCDA-2.0.0"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.decision-deck.org/2009/XMCDA-2.0.0
file:../XMCDA-2.0.0.xsd">
<alternatives>
       <alternative id="a01_SolarPV">
              <active>true</active>
       </alternative>
       <alternative id="a02_Wind">
              <active>true</active>
       </alternative>
</alternatives>
</xmcda:XMCDA>
```

Criteria.xml

```
<xmcda:XMCDA xmlns:xmcda="http://www.decision-deck.org/2009/XMCDA-2.0.0"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.decision-deck.org/2009/XMCDA-2.0.0
file:../XMCDA-2.0.0.xsd">
<criteria>
       <criterion id="c01_IncreaseRETSupply" />
       <criterion id="c02_IRR" />
       <criterion id="c03_PlanningApprovalComplexityRating" />
       <criterion id="c04_VisibilityRating" />
</criteria>
</xmcda:XMCDA>
```

CriteriaWeights.xml


```xml
<xmcda:XMCDA xmlns:xmcda="http://www.decision-deck.org/2009/XMCDA-2.0.0"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.decision-deck.org/2009/XMCDA-2.0.0
file:../XMCDA-2.0.0.xsd">
<criteriaValues mcdaConcept="weights">
	<criterionValue>
		<criterionID>c01_IncreaseRETSupply</criterionID>
		<value>
			<real>0.30</real>
		</value>
	</criterionValue>
	<criterionValue>
		<criterionID>c02_IRR</criterionID>
		<value>
			<real>0.20</real>
		</value>
	</criterionValue>
	<criterionValue>
		<criterionID>c03_PlanningApprovalComplexityRating</criterionID>
		<value>
			<real>0.20</real>
		</value>
	</criterionValue>
	<criterionValue>
		<criterionID>c04_VisibilityRating</criterionID>
		<value>
			<real>0.30</real>
		</value>
	</criterionValue>
</criteriaValues>
</xmcda:XMCDA>
```


PerformanceTable.xml


```xml
<xmcda:XMCDA xmlns:xmcda="http://www.decision-deck.org/2009/XMCDA-2.0.0"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.decision-deck.org/2009/XMCDA-2.0.0
file:../XMCDA-2.0.0.xsd">
<performanceTable>
	<alternativePerformances>
		<alternativeID>a01_SolarPV</alternativeID>
		<performance>
			<criterionID>c01_IncreaseRETSupply</criterionID>
			<value>
				<real>0.96</real>
			</value>
		</performance>
		<performance>
			<criterionID>c02_IRR</criterionID>
			<value>
				<real>0.33</real>
			</value>
		</performance>
		<performance>

	<criterionID>c03_PlanningApprovalComplexityRating</criterionID>
			<value>
				<real>0.6</real>
```

```xml
                </value>
            </performance>
            <performance>
                <criterionID>c04_VisibilityRating</criterionID>
                <value>
                    <real>0.6</real>
                </value>
            </performance>
        </alternativePerformances>
        <alternativePerformances>
            <alternativeID>a02_Wind</alternativeID>
            <performance>
                <criterionID>c01_IncreaseRETSupply</criterionID>
                <value>
                    <real>0.3</real>
                </value>
            </performance>
            <performance>
                <criterionID>c02_IRR</criterionID>
                <value>
                    <real>0.58</real>
                </value>
            </performance>
            <performance>

        <criterionID>c03_PlanningApprovalComplexityRating</criterionID>
                <value>
                    <real>0.2</real>
                </value>
            </performance>
            <performance>
                <criterionID>c04_VisibilityRating</criterionID>
                <value>
                    <real>1.0</real>
                </value>
            </performance>
        </alternativePerformances>
    </performanceTable>
    </xmcda:XMCDA>
```